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LIFE Materials: Fuel Cycle and Repository Volume 11

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LIFE Materials:
Fuel Cycle and Repository
Volume 11

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Executive Summary

Major conclusions from this volume are the following:

The fusion-fission LIFE engine concept provides a path to a sustainable energy future based on safe, carbon-free nuclear power with minimal nuclear waste. The LIFE design ultimately offers many advantages over current and proposed nuclear energy technologies, and could well lead to a true worldwide nuclear energy renaissance. When compared with existing and other proposed future nuclear reactor designs, the LIFE engine exceeds alternatives in the most important measures of proliferation resistance and waste minimization. The engine needs no refueling during its lifetime. It requires no removal of fuel or fissile material generated in the LIFE engine. It leaves no weapons-attractive material at the end of life.

Although there is certainly a need for additional work, all indications are that the "back end" of the fuel cycle does not to raise any "showstopper" issues for LIFE. Indeed, the LIFE concept has numerous benefits:

- Per unit of electricity generated, LIFE engines would generate 20-30 times less waste (in terms of mass of heavy metal) requiring disposal in a HLW repository than does the current once-through fuel cycle.
- Although there may be advanced fuel cycles that can compete with LIFE's low mass flow of heavy metal, all such systems require reprocessing, with attendant proliferation concerns; LIFE engines can do this without enrichment or reprocessing. Moreover, none of the advanced fuel cycles can match the low transuranic content of LIFE waste.
- The specific thermal power of LIFE waste is initially higher than that of spent LWR fuel. Nevertheless, this higher thermal load can be managed using appropriate engineering features during an interim storage period, and could be accommodated in a Yucca-Mountain-like repository by appropriate "staging" of the emplacement of waste packages during the operational period of the repository. The planned ventilation rates for Yucca Mountain would be sufficient for LIFE waste to meet the thermal constraints of the repository design.
- A simple, but arguably conservative, estimate for the dose from a repository containing 63,000 MT of spent LIFE fuel would have similar performance to the currently planned Yucca Mountain Repository. This indicates that a properly designed "LIFE Repository" would almost certainly meet the proposed Nuclear Regulatory Commission standards for dose to individuals, even though the waste in such a repository would have produced 20-30 times more generated electricity than the reference case for Yucca Mountain. The societal risk/benefit ratio for a LIFE repository would therefore be significantly better than for currently planned repositories for LWR fuel.

Several topical reports are being prepared on the materials and processes required for the LIFE engine. Specific materials of interest include:

- TRISO Fuel (TRISO)
- Inert Matrix Fuel (IMF) & Other Alternatives

- Beryllium (Be) & Molten Lead Blankets (Pb/PbLi)
- Molten Salt Coolants (FLiBe/FLiNaBe/FLiNaK)
- Molten Salt Fuel (UF4 + FLiBe/FLiNaBe)
- Cladding Materials for Fuel & Beryllium
- ODS FM Steel (ODS)
- Solid First Wall (SFW)
- Solid-State Tritium Storage (Hydrides)

This Topical Report is Volume 11 in a 12-volume series, which is summarized below.

- Volume 1 – Overview of Fuels & Structural Materials Issues
- Volume 2 – Design & Fabricability
- Volume 3 – Transmutation & Phase Formation
- Volume 4 – Radiation Effects
- Volume 5 – Thermomechanical Effects
- Volume 6 – Corrosion & Environmental Cracking
- Volume 7 – Molten-Salt Coolants
- Volume 8 – Molten-Salt Fuels
- Volume 9 – On-Site Solid-State Tritium Storage
- Volume 10 – Proliferation Resistance
- Volume 11 – Fuel Cycle & Repository
- Volume 12 – Licensability

This report of focused on the thermal, radiological, and cost aspects of disposing of LIFE fuel after it is removed from the LIFE engine. This volume is organized as follows:

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Acronyms and Abbreviations

CDSP – Co-Disposal Package (a combination of high-level waste glass and DOE-owned spent nuclear fuel)

CSNF – Commercial Spent Nuclear Fuel

DSNF – Defense Spent Nuclear Fuel

DU – Depleted Uranium

FI – Fast Ignition

FIMA – Fissions per Initial Metal Atom

GWe – Gigawatt of electrical energy

GWt – Gigawatt of thermal energy

HLW – High Level Waste

HSI – Hot-Spot Ignition

IHM – Initial Heavy Metal

LIA – Low-Incidence Angle

LIFE – Laser Inertial confinement Fusion fission Energy

LWR – Light Water Reactor

MT – Metric Ton

MTIHM – Metric Tons of Initial Heavy Metal

NIF – National Ignition Facility

PWR – Pressurized Water Reactor

TAD container – Transportation, Aging, and Disposal container

TRISO – TRIstructural ISOtropic (fuel particles)

TSPA – Total System Performance Assessment

YME – Yucca Mountain (repository) Equivalent

Chapter A. LIFE Requirements for Fuel Disposal

Issues Facing Light Water Reactor Fuel Cycles

Nuclear power has been criticized on both safety and waste disposal bases. The safety issues are based on the potential for both plant damage and environmental effects, due to either nuclear criticality excursions or loss of cooling. Redundant safety systems are used to reduce the probability and consequences of these risks for LWRs. Laser Inertial confinement Fusion fission Energy (LIFE) engines and LIFE nuclear waste are inherently subcritical, reducing the need for systems to control the fission reactivity. LIFE engines also have two safety systems to remove decay heat in the event of loss of coolant or loss of coolant flow. These features of LIFE are expected to result in a more straightforward licensing process and are also expected to improve the public perception of risk from nuclear power generation, transportation of nuclear materials, and nuclear waste disposal.

Waste disposal is an ongoing issue for LWRs. The conventional (once-through) LWR fuel cycle treats unburned fuel as waste, and results in the current U.S. fleet of LWRs producing about twice as much waste in their 60 years of operation as is legally permitted to be disposed of in Yucca Mountain. Advanced LWR fuel cycles would recycle the unused fuel, such that each GWe-yr of electricity generation would produce only a small waste volume compared to the conventional fuel cycle. However, advanced LWR fuel cycles require chemical reprocessing plants for the fuel, multiple handling of radioactive materials, an extensive transportation network for the fuel and waste, and careful attention to not producing weapons-attractive materials at any point within the fuel cycle. In contrast, the LIFE engine requires only one fueling for the plant lifetime, has no chemical reprocessing, has no uranium enrichment, and has only a single shipment of a small amount of waste at the end of the fuel life (nominally 50 years). Public perception of the nuclear option will be improved by the reduction in the number of shipments of radioactive material per GWe-yr and the elimination of the need to build multiple repositories that is afforded by the LIFE concept. In addition, LIFE fuel requires neither enrichment nor reprocessing, eliminating the two most significant pathways to proliferation from commercial nuclear fuel to weapons programs.

LIFE Waste and the Phases of its Disposal

For the purposes of this document, we have assumed that spent fission fuel from a LIFE engine consists of 2-cm-diameter pebbles that contain TRISO particles. (Other concepts for the LIFE fission fuel that are capable of ultra-high burnups are also under development.) At the time of disposal, the TRISO particles contain a mixture of the original fuel and structural materials, fission products, actinides produced by neutron capture in the fuel, and nuclides produced by the in-engine decay and activation of the fission products and actinides. A range of fertile and fissile fuels is being considered for the LIFE engine. This initial report focuses on the use of depleted uranium as the fuel.

Disposal of spent LIFE fuel will be accomplished in two phases. The initial (interim storage) phase begins when the spent LIFE fuel pebbles are removed from the LIFE engine and ends when the spent LIFE fuel is emplaced in a repository. The final (repository) phase begins when the spent LIFE fuel is emplaced in a repository.

The initial phase must last at least five years because that is the minimum age allowed for disposal in U.S. repositories [Public Law 97-425, 1982]. During the initial phase, the heat generation rate of LIFE pebbles is high enough that the pebbles must be immersed in a coolant, such as the LIFE engine coolant.

The repository phase can begin at five years or later, depending on design tradeoffs between the two phases. Because the repository design requirements are most challenged for younger waste, spent LIFE fuel pebbles that have been out of the LIFE engine for five years are the basis of the initial design effort for disposal.

For the depleted uranium LIFE fuel, two point designs were available during the time of this study. These two designs have TRISO particle diameters of 958 and 994 microns, respectively, and each has been used in parts of this volume. Both TRISO particles have the same 600-micron diameter UCO kernel, but the larger TRISO particle has a thicker SiC shell layer. Because both TRISO particles have the same 0.3 packing fraction in a LIFE pebble, there is more uranium in a pebble composed of smaller TRISO particles, and hence fewer pebbles in a LIFE engine (13.8 million) and fewer waste packages (9.37) to dispose of those pebbles. The smaller TRISO particles (958-micron diameter) were used in the cost section of this volume.

For pebbles composed of larger TRISO particles (994-micron diameter), there are more pebbles in a LIFE engine (15.4 million) and more waste packages (10.47) to dispose of those pebbles. The larger TRISO particles were used in the thermal and radiological sections of this volume.

Chapter B. Summary of Existing Knowledge

Interim Storage

Development of the design of the interim storage phase will be initiated after the repository design is worked, because the interim storage equipment has close interfaces with both the LIFE engine design and the repository design.

The heat load during interim storage will likely require the pebbles to be immersed in a heat transfer medium, such as the molten salt coolant used for the LIFE engine. The design for the off-normal dumping of pebbles in the LIFE engine will be the starting point for the interim storage design.

The duration of interim storage depends on the repository design. The approach being taken for initial LIFE designs is to minimize the interim storage period and to design the repository to dispose of spent LIFE fuel after only five years of interim storage.

During the interim storage period, which is at least the first five years after removal from the operating LIFE engine, the thermal power from the fission product decay in the pebbles will require immersing the pebbles in a heat-transfer medium. The vessel under the LIFE engine, which is designed to cool the pebbles during a loss of coolant situation, could be used. If the LIFE power plant is being decommissioned, interim storage in that vessel would be appropriate. If the LIFE power plant is being refurbished with new hardware for a second generation of LIFE power production, that vessel or a similar vessel could be used at an on-site location for the interim storage.

Once the fuel is removed from the LIFE engine system, it may be necessary to store it for an additional period of time before repository disposal. For calculation purposes, we have conceptualized this interim storage thermal system as packing the pebbles into cylindrical containers the same size as the Transportation, Aging, and Disposal (TAD) containers developed for the Yucca Mountain repository. The 40% of the volume that is between the pebbles would be filled with a static heat-transfer fluid during the interim storage period (with the fluid having the same thermal conductivity as the pebbles for the initial calculations). The interim storage containers (10.47 of them, for a 40 metric-ton depleted-uranium LIFE engine) would be lined up in a circular conduit (with the conduit and container centerlines coincident). The conduit would be cooled with forced air ventilation, at a rate in which the air temperature would increase from 25ºC at the inlet to 60ºC at the exit of the conduit. An axial cooling air velocity of 1 m/s sequentially along the line of containers was arbitrarily chosen for the 5-year power, allowing sizing of the flow channel (4.2 m diameter). The air flow rate will be high initially, but can be reduced as the spent LIFE fuel thermal power decays (decreasing from 28.7 to 5.2 kW/m^3 after 5 years). The air flow rate is calculated from the heat capacity of the air, the desired inlet and exit air temperatures, the power of the line of containers, and the surface area of the cylindrical sides of the containers. For the initial calculation, the axial air velocity decreased from an initial value of 12 mph to only 2 mph after 5 years.

The calculation assumes quasi-steady-state at each time (0, 1, 2, 3, 4, 5, and 10 years). The convective heat transfer, $q''_{r=a}$, from the container surface (at $r = a$) to the air is

$$q''_{r=a} = h_{air} (T_{od} - T_{air})$$

The heat transfer coefficient is taken from the Nusselt Number ($Nu = h_{air} D_h / k_{air}$) where D_h is the hydraulic diameter of the annulus and k_{air} is the thermal conductivity of the air. The Nusselt Number is taken from the Dittus-Boellter correlation ($Nu = 0.023 Re^{0.8} Pr^{1/3}$). The Reynold's Number, Re, is $[(4/\pi) m_{air} / (D_h \mu_{air})]$ where m_{air} is the air flow rate in kg/s and μ_{air} is the dynamic viscosity. The Prandtl Number, Pr, for air is 0.707. Conservatively using the exit temperature for the air (rather than the local temperature at the position of each container), the container surface temperature can be calculated from the heat transfer coefficient, the container power, and the surface area of the cylindrical shell of the container. Radiation to the conduit and then convection into the air or conduction to the surrounding environment is conservatively not included in this initial model.

The quasi-steady-state temperature profile across the container shell thickness and through the static fuel plus heat transfer fluid to the centerline can be calculated by combining the well-known solutions to the steady-state radial transport equations for heat transfer (across an annulus and across a cylinder) [Carslaw and Jaeger, 1959]. The result of combining these equations is

$$T_{\max} = T_{od} + \left\{ \frac{q''_{r=a}}{k_{metal}} \right\} \times \left\{ a \ln\left(\frac{a}{b}\right) \right\} + \left\{ \frac{q''' b^2}{4k_{fuel}} \right\}$$

The quantity $q''_{r=a}$ is the heat flux (W/m^2) on the outer surface of the container, which was calculated above from the container power and surface area. The property k_{metal} is the thermal conductivity of the metal container shell, q''' is the power density in the volume occupied by the fuel (W/m^3), k_{fuel} is the effective thermal conductivity of the fuel mass (including the heat transfer fluid), a is the outer radius of the container, and b is the outer radius of the fuel mass (inner radius of container).

The results of the calculation are shown in Figures 1 and 2. The required ventilation rate is reasonable, and will decrease as the spent LIFE fuel decays. Peak container temperatures are below 450°C, and peak spent fuel temperatures are below 500°C. The fuel is well within its thermal limit, which will be in the 700-1400°C range, with the location in this range still being determined. The container temperature is higher than the current limit for Yucca Mountain, and hence it is likely that the interim storage container will not be a TAD that can be emptied of the static heat transfer fluid (which may not be suitable for the duration of repository performance period). Rather, at the end of interim storage, the spent LIFE fuel will be removed from the (high-temperature-tolerant) interim storage container and emplaced in a TAD, with air or inert gas filling the 40% of the container volume between the pebbles. The TAD can then be shipped to the repository, mated with a waste package, and emplaced underground.

Repository

The performance for spent LIFE fuel is discussed first from a thermal perspective, then from a radiological perspective, and finally from a non-proliferation perspective. The section concludes with a discussion of the cost of disposal.

Repository Thermal Aspects

The repository thermal discussion is organized into sections discussing the thermal design requirements for the repository, the preclosure performance, and the postclosure performance.

The preclosure performance discussion includes both normal (ventilated) operation and off-normal (loss of ventilation) operation. The postclosure performance discussion includes both intact drift and collapsed drift situations.

Thermal performance includes the temperature history at each of the temperature constraint locations: mid-pillar, drift wall, waste package surface, and LIFE pebble (waste package centerline).

Repository Thermal Constraints

For the initial LIFE repository calculations, it is assumed that the repository site and design will be similar to that of the proposed Yucca Mountain repository. Yucca Mountain is designed to dispose of 63,000 metric tons of light water reactor (LWR) spent nuclear fuel, and also 7,000 metric tons of DOE owned high level waste [Sandia 2007a]. The DOE-owned high level waste is one-third spent nuclear fuel from naval and research reactors and two-thirds reprocessed high level waste in the form of vitrified waste. The models used to calculate Yucca Mountain repository performance have been modified in this report to consider the differences in the LIFE waste form.

The Yucca Mountain design (Figure 3) consists of a series of parallel drifts (tunnels) on 81-m centers, with lengths ranging from ~400 to ~800 m, depending on the location within the footprint. There are 108 emplacement drifts with total length of 65.273 km [Sandia, 2007a].

The Yucca Mountain Program has adopted "thermal constraints" on the allowable temperatures at four locations to assure that the natural (site) and engineered features of the repository perform within their design envelopes. The first constraint is that the temperature at the midpoint between the drifts (40.5 m from the drift centerline, and called the mid-pillars) will remain below the boiling point of water at the repository altitude (96°C), such that liquid water percolating through the mountain will have a sub-boiling pathway through the elevation occupied by waste packages (the repository horizon).

The Yucca Mountain emplacement drifts (tunnels) will be 5.5 m in diameter, and the characteristics of the tuff rock minerals impose a second limit of 200°C at the drift wall. If this limit is exceeded for long periods of time, some minerals may transform to a mineral phases with higher specific volumes, which could lead to spalling of rock from the drift walls.

Each Yucca Mountain drift will emplace a line of waste packages, with small, 10-cm gaps between them. The waste packages will be cylindrical, with a length of 5.8501 m and an outside diameter of 1.8816 m [Sandia, 2007b]. The waste packages will be double walled with a 1-inch-thick outer corrosion barrier of Alloy-22 (C-22), and a 2-inch-thick inner structural vessel of stainless steel 316 [Sandia, 2007a]. If the Alloy-22 temperature exceeds 300°C for extended periods of time, Mo-rich μ and P phases can form that deplete the surrounding matrix of corrosion-resistant elements [Torres, 2008].

A TAD container will be loaded with waste at the utility site, transported in a reusable shipping cask to the repository, and then sealed into a waste package. The material for the TAD container will be stainless steel for LWR waste, but may be a different material for spent LIFE fuel.

There is a fourth temperature limit imposed on LWR waste to protect the Zircaloy cladding, and there will almost certainly be a similar limit on spent LIFE engine waste to ensure stability of the spent fuel from a LIFE engine. That limit has not been set at this time, but is likely to be between 700°C and 1400°C.

The thermal constraints are shown schematically in Figure 3. The figure shows commercial spent nuclear fuel (CSNF) waste packages that can contain either 21 pressurized water reactor (PWR) assemblies or 44 boiling water reactor (BWR) assemblies. The figure also shows co-disposal (CDSP) waste packages that contain vitrified high-level waste and DOE spent nuclear fuel. The baseline design for Yucca Mountain accommodates 11,162 waste packages [Sandia 2007a]. The 7483 CSNF waste packages dispose of 63,000 metric tons of initial heavy metal (MTIHM, also referred to as MTU, metric tons of uranium, in some references). The remaining 3279 CDSP waste packages and 400 naval spent nuclear fuel waste packages dispose of 7,000 MTIHM. The total system performance assessment (TSPA) [Sandia, 2008] for Yucca Mountain increases these waste package quantities by about 4% to conservatively fill all repository drifts, including contingency space, in the calculation [Sandia, 2007a]. On average, a CSNF waste package produces significantly more heat than a CDSP waste package

If a LIFE repository is the second repository built in the United States, it will likely include CDSP waste packages, because there is more vitrified high-level waste than can be accommodated in the Yucca Mountain DOE waste allocation (10% of 70,000 MTIHM) [USDOE, 2008a]. Initial repository thermal calculations for spent LIFE fuel conservatively ignore the low-power CDSP waste packages.

Preclosure Ventilation - Normal Operation

The thermal decay curve for spent LIFE fuel is different than for CSNF because of the different radionuclide composition of these waste streams.

The spent LIFE fuel is assumed to fill the interior volume of the TAD canisters at 60% packing fraction. For a base case TRISO particle diameter of 994 μm, 10.47 waste packages will contain the inventory of spent fuel from one LIFE engine (40 metric tons of depleted uranium). For a LIFE engine power history that results in 99% fissions per initial metal atom (FIMA), the thermal power of the spent LIFE fuel at 5 years (the youngest spent fuel allowed to be emplaced in a repository) is 13.7 kW/MTIHM, which corresponds to a thermal output of ~52 kW per waste package or a linear power density of 8.8 kW/m in the repository emplacement drifts.

Figure 4 compares the LIFE and Yucca Mountain heat loads. The LIFE repository is shown, conservatively, at five years after irradiation of the fuel ceases. In contrast, the CSNF waste is shown beginning at 23 yr out of reactor, the expected situation for Yucca Mountain. At 23 yr, the combined average CSNF/CDSP thermal load in a Yucca Mountain emplacement drift is 1.45 kW/m. At that point in time, spent LIFE fuel has decayed to 4.3 kW/m (from its five-year value of 8.8 kW/m). At about 130 yr after power plant operation (which is ~100 yr in the repository for CSNF), the waste packages for the two waste streams have roughly equal power. The spent LIFE fuel is cooler than LWR waste at later times because the spent LIFE fuel has a much lower actinide inventory, which dominates the CSNF thermal power at later times. Figure 5 shows the decay curves from three potential LIFE waste streams and LWR waste; the slopes of the decay curves are roughly parallel after 1000 yr, when actinides dominate the thermal power.

The Yucca Mountain repository design uses ventilation during the ~100 year preclosure period to remove most (80-90%) of the heat from the waste packages. After closure, thermal conduction into the repository rock is adequate to remove the waste package heat (which has decayed to lower levels) while remaining within the four thermal constraints (mid-pillar, drift wall, waste package surface, and CSNF cladding).

Because the thermal output of spent LIFE fuel is higher than that of CSNF during the preclosure period, the design must be modified. Options include larger gaps between the waste packages, increasing the time between discharge and repository emplacement of the spent LIFE fuel, reducing the quantity of spent fuel in each waste package, increasing the ventilation rate, or phasing the emplacement of the LIFE waste packages into the drifts. Phased emplacement is being evaluated initially because it can be handled operationally, with essentially no increase in repository or interim storage costs.

Waste Package Surface Temperature

Thermal calculations for a LIFE repository similar to the CSNF/CDSP Yucca Mountain repository were conducted for the preclosure period. During this period, active forced ventilation is used to control temperatures within and around the emplacement drifts. The preclosure ventilation model developed for the License Application for Yucca Mountain was used and modified, as appropriate for LIFE waste packages, to calculate the time histories of waste package, drift wall, and ventilation air temperatures.

The ventilation model [Bechtel, 2004] includes thermal radiation from the surface of the waste package to the drift wall, convection to the ventilation air from the surfaces of the waste package and the drift wall, and conduction within the rock mass surrounding the emplacement drift. These processes were modeled using analytical techniques that assume quasi-steady-state at each time step, a series of well-mixed volume elements along the repository drift, and the principle of superposition to calculate the temperature response of the rock mass due to a heat flux. The use of the quasi-steady-state approximation allows the energy-balance equations to be written without time derivatives, resulting in algebraic solutions to the various components of the thermal energy balance. The progress of the calculation through time is like that of integrating a function using Euler's method, summing a "stair-step" approximation. The drift is divided along its length into volumetric elements, and the properties are assumed to be well-mixed in each volume element such that the variable of interest (*i.e.*, temperature) is everywhere the same within the element. Application of the superposition technique for the heat transfer within the surrounding rock mass is based on scaling and time-shifting of the temperature response of the drift wall to a short-duration constant flux (a Greens' Function approach). The single temperature response is the higher of the temperature increases for two analytical solutions [Carslaw and Jaeger, 1959]. The solutions are for a region bounded internally by a circular cylinder and for a semi-infinite slab; the cylinder solution is higher for the first twenty years. The analytical temperature response is scaled using the heat flux from the waste package at the time of interest, and the response to a short-duration constant flux is combined with the responses for the prior time steps. A convective heat transfer coefficient of 5.7 W/m^2K, indicative of mixed natural and forced convection, is used in the model. Both the natural and forced convection components of the heat transfer fall within their respective turbulent regimes.

Due to the increased thermal output of a LIFE waste package compared to a CSNF waste package, a phased emplacement scenario was developed for LIFE waste packages. Each drift will be loaded from the back (air exit) to the front (air entrance and loading entrance), in 125-meter long sections, with ten years of ventilation before the next section is loaded. This is in contrast to the filling of an entire single drift within a short period (a few months) for the proposed Yucca Mountain repository. The section-loading technique for LIFE ensures that ventilation air will cool the youngest (highest thermal power) waste packages in the most recently emplaced section, and then the somewhat heated ventilation air will cool the next most recently emplaced section (which has had 10 years to decay to lower power), *etc.* Each 125-meter long section of drift contains 21 LIFE waste packages with 10 cm gaps between packages, representing the spent LIFE fuel from two LIFE engines. Five loadings, emplaced 10 years apart, would fill a typical 625-meter long drift in 40 years. For a higher-volume waste stream, the repository operator would fill multiple drifts simultaneously, maintaining a ten-year in-drift cooling period between phases for each drift. A ventilation flow rate of 15 m^3/s is used in each drift, which is the same ventilation rate used for the License Application for Yucca Mountain.

The Yucca Mountain ventilation calculation assumes simultaneous loading of the drift, and hence is not directly usable for LIFE waste packages emplaced in phases. Three variations in the implementation of the ventilation model were employed to calculate the thermal histories of LIFE waste packages with phased emplacement.

In Variation 1, the first 125-meter long drift section (nearest the air exit) was loaded with 21 LIFE waste packages at time zero, and ventilated for 10 years, which corresponds to spent LIFE fuel aged 5 to 15 years after removal from the power plant neutron flux. The 125-meter long section was divided into eight well-mixed volume elements of approximately 15.6 meters in length. Waste package, drift wall, and ventilation air temperature histories were calculated. The thermal conditions (*i.e.*, drift wall and ventilation air temperatures) calculated by the ventilation model for this first loaded section at ten years are representative of each section ten years after it is loaded, because each of these sections has the same 5-year initial waste age and each is cooled by fresh ventilation air for its first ten years of emplacement. The second decade of ventilation of each 125-meter long section of drift was then calculated, with a heat source for 15 to 25 year-old spent LIFE fuel, inlet air temperature matching the exit air temperature from year 10 of the first section, and an initial drift wall (and rock domain) temperature matching the 10-year drift wall temperature at the exit end of the first section. This procedure was continued until all five sections were loaded (*i.e.*, until 40 years after the start of emplacement). The final segment calculation was continued for an additional 50 years yielding a total of 90 years of preclosure ventilation.

The waste package, drift wall, and ventilation air temperature histories at the exit end of the first section emplaced (the section nearest the end where the ventilation air exits) are plotted in Figure 6. When each of the second through fifth sections are emplaced in front of this first section (at 10 through 40 years, respectively), the temperature of the ventilating air increases sharply (due to its interaction with the newly emplaced waste packages), and then decreases as the thermal power of the waste packages decays. The figure shows that the initial choice of ten years between emplacements is reasonable, because each temperature peak is roughly the same. The last waste package in the drift reach temperature peaks in the 170 to 190°C range at the end of each decade, providing substantial margin to the 300°C limit on waste package surface temperature. The drift wall peak temperature is about 165°C, with significant margin to its 200°C limit.

The results of Variation 1 indicate that the young LIFE waste packages can be accommodated by a reasonable emplacement operation using the Yucca Mountain ventilation design. If more than two LIFE engines are providing waste in each ten-year period, the repository operator would load multiple drifts. For example, if 20 LIFE engines were being serviced in a ten-year period, the repository operator would load Section 1 of Drifts 1 through 10 (waste from two LIFE engines per drift section), and then ten years later proceed to load Section 2 of those same drifts with the waste packages from the next set of 20 LIFE engines.

Variation 1 has two approximations that limit its realism. First, it uses the 10-year drift wall temperature from the exit end of the first section (*i.e.*, the first decade of each section) as the initial temperature of the entire rock domain for that section for the second decade (because the conduction model must start from an isothermal state). This approximation should result in higher predicted temperatures than one would see in a repository because the energy to "preheat" the entire rock domain is a computational artifact and not derived from the heat source. The second approximation is the use of the 10-year exit temperature from the preceding section as the initial (second decade) air inlet temperature. Because the air temperature in a given section and decade quickly spikes and then slowly decays, this approximation provides overly cool air at the start of the second decade, which should result in lower predicted temperatures than one would see in a repository. It also artificially maintains high temperatures after emplacement is complete if the ventilation calculation is extended in time, because the ventilation air source for the final section will not be able to be reduced below that of the end time of the fourth decade, even when the waste package heat source has decayed to levels that would not heat the ventilation air to that level.

Variation 2 used the same mathematical model in a single calculation (with a duration that included the full 90 years). Each 125-m emplacement section was represented by a single well-mixed volume element. The heat source for each volume element was zero until the element was emplaced, and began with the decay curve at 5-years of age. Thus, this calculation is correct for heat source, initial conditions, and boundary conditions. However, it uses coarse zoning compared to Variation 1. Figure 7 shows a similar pattern of temperature histories to that of Variation 1.

Variation 3 used the same 15.6-m volume elements as Variation 1. The air inlet temperatures were improved to be time dependent. The time-dependent exit air temperatures for the preceding section were used as the time-dependent inlet air temperatures over the ten-year period. For example, the air exit temperatures from Section 1 in years 1 to 10 were the time-dependent air inlet temperature for the second section being calculated (which is the second decade of the first section emplaced); this is appropriate because section 1 in years 1 to 10 is identical to section 2 in years 11 to 20, with the exact same initial conditions and heat source). The drift wall temperature initial condition was ambient for each section being calculated. This approximation, which ignores heating of the rock section in the prior decades, is the opposite of Variation 1, which extended the prior drift wall heating to the entire rock domain. Figure 8 shows a similar pattern of temperature histories as the other two Variations.

Figures 9, 10, and 11 compare the temperature histories calculated with the three Variations, for the waste package, drift wall, and ventilation air, respectively. The temperature histories are at the exit end of the drift. The waste package temperature comparison shows that the initial temperature spike and the temperature decay within any decade are both less for Variation 1 than for the other two calculations. This is reasonable because Variation 1 has a constant air inlet temperature that is taken from the end time (lowest value) of the upstream Section, whereas the other two Variations use a time-dependent air inlet temperature that is higher at the start of the decade than at the end of the decade. Variation 1 also shows much slower temperature decay during the 50 years after the last emplacement, because the inlet air temperature into the final section is pinned at a single value rather than being allowed to decrease as the thermal power of the upstream sections decrease. Said another way, the final temperature is asymptotic to this pinned temperature of about 130°C, rather than to the ambient inlet air temperature of 23°C. Based on these observations, Variation 1 will not be used for further calculations.

Turning now to the comparison of the results from Variations 2 and 3, it is clear from Figures 9, 10, and 11 that the loss of spatial resolution in Variation 2 did not compromise the results. The curves are nearly identical, with the exception of a slightly higher initial temperature spike in the later decades for Variation 3. Thus, Variation 2 (which is much easier to set up and run) will be used for most calculations, and Variation 3 will be used only when the initial spike temperature is important.

Figure 12 shows a snapshot of the temperatures along the drift length at 50 years after start of emplacement. The results of the Variations 2 and 3 match well at each location common to the two models. The finer spatial resolution of Variation 3 shows the waste package and drift wall temperature decreases from a more newly emplaced section of the drift to the next section (which was emplaced earlier and hence has decayed to a lower thermal power). Variation 2 does not capture this detail, but produces a consistent result at the end of each section of the drift. The end of each section is the location at which the air heating is forced in the model to balance the difference in the source power and the power conducted into the wall over the entire length of the section (or in each of the set of 8 subsections in Variation 3).

The model results discussed above were generated from Excel spreadsheet files. In Variations 1 and 3, there are five linked files, called Loads. Each load represents another decade for the first section emplaced (at the exit end of the drift). At fifty years, that section has had 10 years each of the five loads, sequentially. Load 1 (the first decade) also represents the first decade of each upstream section. Thus, at fifty years, the last section emplaced (nearest the drift entrance) has had 10 years of Load 1, only. Each file has a computational sheet for each of the eight subsections in the load. These sheets sequentially feed each other, with exit air in one being entrance air temperature in the next. The sheets have a row for each time step, and the blocks of calculations implementing the energy balance are repeated iteratively within the sheet because the linearized radiation heat transfer coefficient requires knowledge of the output (the waste package and drift wall temperatures). This is handled by estimating the temperatures, calculating the radiation heat transfer coefficient, calculating the convection, conduction, and radiation, and using the energy imbalance to heat the ventilation air. The result is the set of waste package, drift wall, and air temperature values (after heating) that produce the energy balance. The process is then repeated using the resulting temperatures to refine the radiation heat transfer coefficient. Although 5 or 6 iterations (depending on the spreadsheet) are used, the results are quite stable after only 2 or 3 iterations. The spreadsheets also display the energy balance for each time step, and graphically display the temperature histories in each subsection, which allows for checking and confidence building.

For Variation 2, there is only one file, and the five sections of the drift are analogous to five subsections in the other two Variations. This means that the energy balance is over the average of a five-times longer portion of the drift, and thus the drift wall and waste package temperatures are the average of a longer portion of the drift. The results indicate that Variation 2 is adequate for most purposes.

It should be noted that two of the four temperature constraints were evaluated in this report section, for the preclosure period (waste package surface temperature and drift wall temperature). The LIFE pebble temperature is evaluated in the next subsection, and the mid-pillar temperature is evaluated in Section B.2.1.3

LIFE Pebble Temperature

A model similar to the interim storage model was developed for the pebble temperatures after emplacement in a repository. The repository model does not include a heat-transfer fluid between the pebbles. Because the pebbles have only a small contact area with each other, radiation between pebbles will contribute significantly to the heat transfer. Natural convection of the gas in the 40% of the volume of the TAD that is between the pebbles is another potential heat transfer mode. The bounding model developed for initial calculations consists of a series of 2-cm-thick cylindrical annuli composed of the pebble material. The annuli are separated by narrow gaps across which radiation must carry the heat. This configuration, although geometrically different than pebbles with minimal surface contact, is expected to bound the centerline temperature because radiation heat transfer is in series, rather than in parallel with conduction. For the convection heat transfer contribution, the centerline and surface temperature results from the radiation:conduction model (at each selected time for the quasi-steady-state calculation) were used in a bounding natural convection model. This two step approach demonstrated that natural convection will not carry a significant fraction of the heat flux from the centerline to the inside surface of the TAD.

The results of the pebble temperature model are shown in Figure 13, based on a boundary condition of 200ºC at the TAD inner surface. Most of the temperature increase is across the gaps, with the outermost gap having the largest temperature increase (because it carries the thermal power of all of the fuel rings and because it is at the coolest, least radiation-efficient, temperature due to the external cooling). Peak pebble temperatures at the centerline at five years fuel age are about 915°C. The temperature limit for the pebbles has not been finalized; however, it is likely to be between 700 and 1400°C. If the pebble temperature limit is at the low end of this range, interim storage of spent LIFE fuel would need to be extended to about 25 yr, similar to the *de-facto* operational scenario for LWR waste in Yucca Mountain. Alternatively, the ventilation rate could be increased, and/or a conductive filler could be added to the waste packages.

Preclosure Ventilation - Loss of Flow Consequences

Most *off-normal repository events* (flooding, high-magnitude earthquakes, volcanism, meteor impact) are of sufficiently low probability that they can be screened out of the safety analysis. The most significant off-normal repository event to be considered for the preclosure period is a loss of ventilation power. The thermal time constants for the repository are sufficiently long that loss of ventilation can be tolerated for over a month for the existing Yucca Mountain design. Because of the higher thermal power of young spent LIFE fuel, the allowable period of non-ventilation will be shorter than for 23-yr-old LWR waste. If appropriate, the LIFE repository design would include emergency generators and redundancy for the ventilation fans to ensure the waste package temperature will not exceed the 300°C limit for a significant period.

Waste Package Surface Temperature

The analysis of waste package surface temperature during loss of ventilation will be performed in FY09.

LIFE Pebble Temperature

The model developed for normal operations is suitable to calculate the interior temperatures of waste packages during off-normal situations, by simply changing the boundary condition at the inside surface of the TAD (it should be noted that the temperature at the inside surface of the TAD is within a few degrees of the outside surface of the waste package due to the high thermal conductivity of the TAD and two waste package layers). The results of the off-normal calculation are shown in Figure 14. The peak pebble temperature is about 925°C. For a pebble temperature limit at the low end of the 700 to 1400°C range, the limit would not be exceeded if the ventilation loss occurred after the age of the spent LIFE waste reached 28 yr. For a pebble temperature limit above ~900°C, even young (5-yr-old) spent LIFE fuel would not exceed the limit if the waste package surface temperature does not exceed 300°C. A longer interim storage period or additional ventilation capacity and redundancy could be used if the pebble temperature limit is at the low end of the potential range.

Postclosure Thermal Performance

Postclosure thermal performance of the repository relies solely on the heat sink of the repository rock (and ultimately of the mountain surface and water table). At about 130 yr age, spent LIFE fuel and LWR waste have the same thermal power (per meter, in Yucca-Mountain-style waste packages). After that time, spent LIFE fuel requires less cooling than LWR waste to stay within the four repository thermal limits. The pebble, waste package surface, and drift wall limits have been discussed above; the mid-pillar (midway between the repository emplacement drifts) temperature is the remaining limit, and is the controlling limit for postclosure thermal performance. To avoid impeding drainage of percolating water through the repository horizon, the mid-pillar temperature should not exceed the boiling point of water (96°C at the repository elevation) for significant periods of time (and for extended lengths of the mid-pillar). At Yucca Mountain and for LWR waste, the mid-pillar temperature reaches ~70°C about a century after repository closure (waste age ~175 yr), and peaks near the boiling point of water about five centuries after repository closure. Because most (80-90%) of the preclosure thermal power spent LIFE fuel will be removed from the repository by the ventilation air, it is the postclosure thermal power that will drive the temperature history at the mid-pillar. The spent LIFE fuel thermal power will be less than that of LWR waste almost immediately after closure; therefore, it is not expected that the mid-pillar temperatures in a LIFE repository will exceed those in a Yucca Mountain LWR repository.

Repository Radiological Aspects

The radioactivity, isotopic makeup, thermal output and radiotoxicity of spent LIFE fuel are compared to the average LWR fuel in the following sections. The LIFE spent fuel discussed here is the material produced by burning 40 metric tons (MT) of TRISO-based fuel using depleted uranium (DU) as the initial heavy metal (IHM). The dimensions and U loading of the fuel is given in **Error! Reference source not found.**. Neutron and photon transport calculations were performed using the Monte Carlo transport code MCNP5 [Los Alamos, 2003]. Burnup calculations were performed using Monteburns 2.0 [Poston and Trellue, 1999], which, in turn, uses ORIGEN2 [Croff, 1983] for depletion/decay calculations. Improvements to Monteburns, as well as additional custom code developments, were required to perform the burnup calculations for LIFE. The nuclear data used were from ENDF/B-VII [Chadwick *et al.*, 2006]. Additional details of the burn calculations can be found in [*Kramer et al.*, submitted]. The burnup as a function of time for this case is shown in Figure 15, and the burnup, burn time, and cumulative thermal energy for this case are tabulated in

Table **1**.

The average LWR fuel used for comparison is based on the projected initial inventory of PWR and BWR fuels (average age of 23-years since discharge) used for the Yucca Mountain Final Environmental Impact Statement USDOE, 2002]. The initial inventory was decayed out to 1 million years using the decay capabilities of ORIGEN-S [ORNL, 2006]. The calculated activity and isotopic makeup of this average LWR fuel is given in Appendix 4 of this Volume.

Volumetric Characteristics

Using the data in Table 1, and assuming that the 2-cm TRISO pebbles can be packed in storage or disposal containers with a packing fraction of 0.6, then each 1 MT of IHM of spent LIFE fuel from the fission blanket will occupy a volume of approximately 2.7 m^3 (see Figure 16). The standard waste package contemplated for use at the candidate Yucca Mountain repository has an internal volume of 10.26 m^3, and 7472 such packages will be required to hold the 63,000 MTIHM of spent LWR fuel (consisting of both BWR and PWR assemblies) that would ultimately be emplaced in the repository. On average, then, one Yucca-Mountain-Style waste package holds 8.43 MTIHM of spent LWR fuel with an average burnup of ~ 38.5 GWt-day/MT (more specifically, ~ 9.0 MTIHM for 21 spent PWR fuel assemblies with an average burnup of 41.2 GWt-d/MT, or ~7.6 MTIHM for 44 spent BWR fuel assemblies with 33.6 GWt-d/MT average burnup) or 3.8 MTIHM of spent LIFE fuel. Strictly on the basis of the volume occupied by a given mass of initial heavy metal fuel in a waste package, LIFE waste with the characteristics given in Table 1 is less than half as "dense" as average LWR fuel. However, in terms of the volume of waste per unit of net electrical energy produced, the situation is quite different. As shown in Table 2 and Figure 17, one Yucca-Mountain-style waste package can hold the spent fuel corresponding to 4438 GWt-days of generated electricity for the case of LIFE waste (at 99% FIMA) while the same waste package represents only 325 GWt-days of energy in the case of average LWR fuel. LIFE waste is therefore about 14 times "denser" in terms of the energy per waste package, and should therefore result in a major reduction, relative to the current once-through LWR fuel cycle, in the repository capacity needed for a given amount of generated energy.

Radiological Characteristics

Specific Activity

The specific radioactivity, in curies per metric ton of initial heavy metal, as a function of time after discharge (age) for the 40 MT TRISO/DU-fueled fast-ignition case is tabulated in Appendices 1-3 to this Volume and summarized in Figure 18a. The specific activity of spent LIFE fuel for all burnups examined is significantly higher than that of average LWR fuel for approximately 300 years after discharge. The specific activity of LIFE fuel with a burnup of 95% FIMA remains above that of average LWR fuel for all times. Spent LIFE fuel with a burnup of 99% FIMA has a specific activity similar to that of average spent LWR fuel up from about 300 years to 100,000 years post discharge, while the 99.9% FIMA LIFE fuel has a specific activity less than that of average LWR fuel from about 300 years to 100,000 years post discharge. At very long times (>300,000 years), the specific activities of the spent LIFE fuels for all three burnups are somewhat higher than that of average spent LWR fuel.

Figure 18b shows the same data, but in this case normalized to the total electrical energy generated by the LIFE or LWR fuel. It is clear from Figure 18b that the radioactivity per-unit-energy-generated of spent LIFE fuel with burnup > 95% FIMA is always less than that of similarly normalized spent LWR fuel, suggesting that the benefit to hazard ratio of LIFE waste is significantly better than that of spent LWR fuel. Nevertheless, the spent fission fuel for a LIFE engine is a hazardous material that will require isolation from the biosphere for at least hundreds of thousands of years. Generation of electrical power by LIFE engines fueled with DU will not obviate the need for long-term geological repositories for the discharged waste.

The general categories (fission products and the four actinide decay chains) of the nuclides contributing to the activity of spent LIFE fuel are shown in Figure 19. For decay times of less than ~300 years, the activity of spent LIFE fuel is dominated by short-lived fission products. Specifically, the activity of the waste (regardless of burnup) from the DU-fueled LIFE engine is dominated by the decay of ^{137}Cs + ^{137m}Ba, and ^{90}Sr + ^{90}Y for the first few hundred years after discharge (Figure 20a). These are the same nuclides responsible for most of the activity of spent LWR fuel during the same time period (though the specific activity of LWR fuel is significantly less).

Between ~300 and a few tens of thousands of years (Figure 19a and Figure 20b), decay of the actinides and their daughter products (^{246}Cm, ^{242}Pu, ^{240}Pu) are the dominant sources of radioactivity in spent LIFE fuel. At times greater than ~20,000 years, fission products (^{135}Cs, ^{93}Zr + ^{93m}Nb and ^{99}Tc) once again become the dominant source of radioactivity. ^{242}Pu is the only actinide that contributes more than 5% of the total activity during the post-100,000-year time period. LIFE waste differs substantially from average LWR spent fuel (Figure 21) in terms of the isotopic makeup of the primary contributors to the activity after a few hundred years of decay. The activity in spent LWR fuel is dominated by ^{241}Am, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{226}Ra (+ daughters), ^{229}Th (+ daughters), and ^{99}Tc decay.

It is instructive to examine the quantity of actinides (specifically, the transuranic elements) present in LIFE fuel as a function of burnup (see Table 3 and Figure 22a). From 20% FIMA to 60% FIMA, LIFE fuel contains roughly 10 times the concentration of transuranic elements than does average LWR fuel at the time of discharge. Between 60% and 95% FIMA, these elements begin to “burn out” in the LIFE engine, and at 95% FIMA, their concentration is a little more than twice that in average spent LWR fuel. By 99% FIMA, they are at a level half that of LWR fuel, and at 99.9% FIMA, they are present at about a tenth the concentration in LWR fuel. When one looks at the production of transuranics as a function of the energy produced by a LIFE engine *vs.* a conventional LWR with no reprocessing, the LIFE engine produces less transuranics per unit energy generated for all burnups greater than ~50% (Table 3 and Figure 22b). Per unit energy produced, a LIFE engine operating to a burnup of 99% FIMA produces ~60 times less transuranics than an average LWR. The bulk of the mass of transuranics in LIFE fuel consists of relatively long-lived isotopes. As will be shown in the next section these are the nuclides that are responsible for the intrinsic long-term radiological hazard of spent fuel; however, for a well designed repository, they are not necessarily the nuclides that ultimately pose the greatest risk to the biosphere.

Radiotoxicity

From the standpoint of radiological hazard, it is not the activity of a nuclear waste that is important; rather, it is the radiotoxicity of the waste that is of concern. Here, radiotoxicity is expressed in terms of the volume of air or water required to dilute the waste to below the maximum permissible concentrations for air and water in the Code of Federal Regulations, 10 CFR 20 [USNRC, 2007a] or public exposure, based on the adult ingestion and inhalation committed dose coefficients of ICRP Publication 72 [ICRP, 1972]. These calculations are easily performed using ORIGEN-S [ORNL, 2006]. The radiotoxicity calculated in this way provides a measure of the *intrinsic* hazard (not risk) of radioactive materials, and provides a repository-independent way of comparing the relative hazards of different radioactive wastes. It does not take into account any physical or chemical properties of the waste (*e.g.*, dissolution behavior or propensity to form aerosols) that could reduce or enhance the possibility of actually receiving a dose from the waste. Furthermore, the radiotoxicity does not take into account any engineered systems (*e.g.*, the engineered barrier system of a geological repository) or natural processes (*e.g.*, dispersion, sorption/retardation, solubility limitations) that would be present in a repository system and which would prevent exposure of the biosphere to the radioactivity of the waste.

Figure 23a compares the specific ingestion radiotoxicities of LIFE waste and average LWR fuel and Figure 23b compares the two waste types on the basis of the radiotoxicity per unit energy generated. Until about 100 years have elapsed from the time of discharge, LIFE waste of all burnups examined has significantly higher ingestion radiotoxicity on a per-MT basis, than LWR spent fuel. After about 100 years of decay, LIFE waste has roughly the same specific radiotoxicity as average spent LWR fuel, depending on the burnup of the LIFE fuels. When normalized to the energy generated, however, LIFE waste with burnup of >95% FIMA has a dramatically lower ingestion radiotoxicity than spent LWR fuel (Figure 23b). This normalization provides a measure of the intrinsic hazard/benefit ratio of the waste, and over the entire period of time relevant to repository performance, the ratio of the ingestion radiotoxicity to generated energy for LIFE waste is 1 to 2 orders of magnitude less than that of spent LWR fuel.

Figure 24 shows the analogous plots for the inhalation radiotoxicity of LIFE waste and spent LWR fuel. For all times between 1 year and 1 million years after discharge, the specific inhalation radiotoxicity for LIFE waste with 99% FIMA is similar to that of LWR fuel; the 95% FIMA case has higher specific radiotoxicity and the 99.9% FIMA case is lower. When normalized to the energy produced, the inhalation toxicity of LIFE waste is, again, 1-2 orders of magnitude less than that of spent LWR fuel, depending on the burnup of the LIFE fuel.

As shown in Figure 25, essentially all the long-term radiotoxicity hazard stems from the decay of the residual actinides in LIFE fuel. This is similar to the case of spent LWR fuel; however, as might be expected from the differences in the radionuclide inventories of these different wastes, the identity of the radionuclides contributing to the hazard are somewhat different for LIFE and LWR fuels. These differences are illustrated in Figure 26, in which the fractional contributions of individual radionuclides to the total ingestion radiotoxicity are plotted as a function of time. Table 4, which lists the nuclides contributing more than 4% to the total radiotoxicity of these wastes at any time between 10^3 and 10^6 years after discharge, summarizes these differences. As opposed to LWR fuel, radiotoxicity of LIFE waste has a significant contribution from ^{129}I, ^{243}Am, ^{246}Cm, ^{248}Cm. Nuclides present in LWR waste that are not significant to the radiotoxicity of LIFE waste include ^{237}Np, ^{210}Pb, ^{225}Ra, ^{226}Ra, and ^{230}Th.

Summary of Dissolution Behavior of TRISO Fuels

It is expected that the spent TRISO fuel pebbles would constitute the final wasteform for TRISO-fueled engines, and that they would be emplaced in a geologic repository in corrosion-resistant waste packages. With the exception of ^{14}C, which will be produced anywhere nitrogen (*e.g.*, as impurities), carbon, or oxygen is present, radionuclides in the spent TRISO fuel pebbles will be sequestered in the fuel kernels, and will remain inaccessible until the protective SiC layer of the TRISO particles is breached. (It is assumed that the carbon composing the body of the pebble is so radiation damaged and porous that it will not provide a substantial impediment to the release of radionuclides.) Corrosion of the SiC layer will not begin until the waste package fails, allowing ingress of an oxidizing atmosphere and aqueous fluids (groundwater). SiC is thermodynamically unstable in the presence of both water and air, and oxidizes to SiO_2 and a carbon-containing species (*e.g.*, CO_2 or CH_4, depending on redox conditions). Eventually, the TRISO particles will be breached, exposing the fuel kernel to water, allowing the leaching/dissolution of that material and subsequent transport of radionuclides from the waste package and engineered barrier system.

There have been very few experimental studies of the corrosion of the protective carbon and SiC layers of TRISO fuels or of TRISO fuel kernels [Gray, 2004; Landesman *et al*., 2004; Cyrille *et al.*, 2005; Morris and Bauer, 2005; Fachinger *et al*., 2006]. Most relevant are the data presented by Fachinger *et al.* [2006] on the dissolution rate of irradiated and unirradiated SiC (as well as graphitic and pyrolytic carbon) in groundwater-like fluids. The dose received by the irradiated samples used in this study was not specified, but the irradiated samples exhibited an increase in the lattice parameter of 0.73% relative to the unirradiated material. Aqueous solutions of various compositions corresponding to a range of groundwaters were used to corrode the SiC at temperatures between 25°C and 180°C. The data show good Arrhenius-law behavior (see Figure 27), with the unirradiated samples having a distinctly lower activation energy than the irradiated samples. Over the range of conditions tested, the dissolution rates ranged from 1.4×10^{-6} to 8.3×10^{-5} gm/m^2/day. For SiC with a density of 3.2 gm/cm^3, these correspond to a range of surface removal rates of ~0.16 to 3.2 micrometers per thousand years. The lifetime (assuming only generalized corrosion) of the 90-micrometer thick SiC layer in the TRISO particles considered for the LIFE engine would therefore be between ~9,500 and 570,000 years. The low end of this range would provide little in the way of a long-term barrier to the release of radionuclides;

however, the upper end of the range represents more than half the proposed statutory period governing the performance of a Yucca Mountain repository, and would have a significant positive impact on repository performance. It is not known how the high dose received by the SiC layer in a LIFE engine would affect the dissolution rate (but it is hard to imagine that it would improve the performance).

The few experiments on the dissolution behavior of TRISO fuel kernels [Landesman *et al.*, 2004; Cyrille *et al.*, 2005; Fachinger *et al.*, 2006] are not relevant to the case of LIFE fuel. The dissolution behavior of TRISO kernels discharged from a "normal" fission reactor is governed by the dissolution of the original fuel matrix (*i.e.*, UO_2, (U, Th)O_2, (U,Pu)O_2) because even under what are considered "high burnup" conditions for such reactors, much of the initial kernel remains unfissioned. In the case of LIFE, the fuel kernel will have been "burned to a crisp", and the kernel will have a chemical composition completely unlike that of the starting fuel (Figure 28). There are no data on the dissolution of material with the projected composition of spent LIFE fuel kernels.

Implications for Performance of a Yucca-Mountain-Style Repository

The proposed NRC Rule (10 CFR 63.311) [USNRC 2005; 2007b] governing the licensing of a repository at Yucca Mountain requires the DOE to show, through performance assessment calculations, that there is a reasonable expectation that the maximally exposed individual receives an annual dose of less than 15 mrem/yr due to releases from the undisturbed repository system for the first 10,000 years after disposal,, and an annual dose of less than 350 millirem between 10,000 and 1,000,000 years. DOE's analysis must include all potential pathways of radionuclide transport and exposure. The Yucca Mountain Total System Performance Assessment (TSPA) [Sandia, 2008] does this. It takes into account all waste types that are destined for this repository. In addition to assessing the nominal performance of the system, it accounts, in a probabilistic manner, for the possibility of early failures of the waste packages and drip shields; seismic events; volcanic eruptions through the repository; igneous intrusions into the repository; and inadvertent human intrusion. The assessment takes into account the kinetics of radionuclide release from the waste, dissolved and colloidal transport through the saturated and unsaturated zones (and in the atmosphere in the case of a volcanic eruption), and the effect of solubility and sorption on release and transport.

Figure 29 [Figures ES-42 and ES-43 from [Sandia, 2008]] summarizes the overall results of the TSPA. The expected total annual dose for first 10,000 years after repository closure is always less than 0.23 millirem/yr, and from 10,000 to one-million years the annual dose is less than 1 millirem/yr. These values are well below the proposed NRC standards.

Figure 29 also shows that the dose during the first 10,000 years after repository closure is dominated by ^{99}Tc, ^{14}C, ^{129}I, and ^{239}Pu. Similarly, ^{239}Pu, ^{129}I, and ^{226}Ra dominate the mean annual dose for the first 100,000 years of the postclosure period, and ^{226}Ra, ^{242}Pu, and ^{237}Np generally dominate the mean annual dose from 100,000 to one-million years. Other radionuclides are significant under specific failure scenarios; these are tabulated in Table 12.

For comparison, Table 13 shows the ratios of the specific activities of these "important" radionuclides in spent LIFE fuel (99% FIMA) to their values for average LWR fuel. In addition, this table lists several radionuclides (^{93}Zr, ^{244}Pu, ^{246}Cm, ^{248}Cm) that, based on their contributions to the radiotoxicity of LIFE fuel, may be important, but were not considered in the Yucca Mountain TSPA because they are not present in significant quantities in the inventory of waste that would be emplaced at Yucca Mountain. Data are not available for ^{14}C and ^{36}Cl in LIFE waste due to limitations of the available burn calculations. Of the fission products of concern, ^{129}I, ^{135}Cs, and ^{93}Zr all have significantly higher specific activities in LIFE waste. Conversely, the specific activities of ^{99}Tc and ^{126}Sn are lower in LIFE waste. With few exceptions, the specific activity of the actinides and daughter products are much lower in LIFE waste than in average LWR fuel. Nevertheless, LIFE waste does have significantly higher activities of ^{242}Pu, ^{244}Pu, ^{246}Cm, and ^{248}Cm.

It is beyond the scope of this report to conduct a rigorous performance assessment of a repository containing LIFE wastes; indeed, it would be impossible to do so at this point. Nevertheless, if we make the following simplifications and assumptions, we can make very crude assessment of the impact of replacing the spent LWR fuel in Yucca Mountain with LIFE waste in the 10,000-year to 1,000,000 year timeframe. (A meaningful assessment for times less than 10,000 years cannot be done because data on the ^{14}C content of LIFE waste are not available.)

- ^{246}Cm is not accounted for independently, but only as its daughter product, ^{242}Pu. This is the same approximation made for the YMP TSPA, but the ^{246}Cm inventory for Yucca Mountain is ~ 8000 times lower than that of LIFE waste. Similarly, we account for ^{248}Cm in the ^{244}Pu activity.
- ^{244}Pu and ^{242}Pu have equal dose conversion factors. This is a good approximation, but it neglects the dose from gamma emissions of ^{240}Np, which is only important for dosed from surface exposure to contaminated soils.
- YMP TSPA results are dominated by the CSNF inventory. This is known to be incorrect – the codisposal packages of DHLW + DOE-SF dominate releases in the TSPA because the physically less robust codisposal packages are more prone to failure due to seismic disturbances.
- Doses scale linearly with radionuclide inventories. This is a very conservative approximation (it will overestimate doses) that is exact for non-solubility-limited, non-sorbing elements; fair for sorbing and colloidally transported elements, and poor for solubility-limited, non-colloid-forming elements.
- The doses from ^{244}Pu (not present in the initial inventory used for the YMP TSPA) can be scaled using the ratio of the mass abundances of ^{244}Pu and ^{242}Pu
- When the LIFE/LWR inventory ratio varies over time, the highest ratio was used for calculations.

- LIFE waste packages and fuel degrade and release radionuclides at the same average rate as the waste considered in the YMP TSPA-LA

- Zr is released from the waste packages and is transported through the subsurface environment at the same rate as Th. Only ingestion routes of exposure to ^{93}Zr are important, and the largest dose-conversion factor for ^{93}Zr (+ ^{93m}Nb) from Sandia [2007c] was used

- 63,000 MT of LIFE waste can be accommodated in the same area of repository as 63,000MT of LWR fuel. This overestimates the quantity of LIFE waste that can "fit" into a given area because a waste package can hold a 2.2 times larger mass of LWR fuel than spent TRISO pebbles (see section above).

The utility of this calculation is largely for the insight into which radionuclides in LIFE waste are likely to contribute significantly to the dose from a repository with characteristics identical to the proposed repository at Yucca Mountain. These results are very much tied to the Yucca Mountain repository; other geologic settings and repository designs could have significantly different results.

The curves in

Figure 29b from the Yucca Mountain TSPA were scaled up or down using the ratios of the activities for 99% FIMA LIFE waste shown in Table 6 and Figure 30a. The doses from ^{93}Zr, ^{244}Pu, and the Cm isotopes were treated as described in the assumptions above. The results are shown in Figure 31a. The doses from a LIFE repository are higher than the YMP TSPA-LA results for this time period, but only by a factor of 4-5. Given the large simplifications and assumptions made in making this calculation, these results should only be taken to mean that releases from a LIFE repository at Yucca Mountain would be roughly comparable to those from the planned repository, and do not come close to approaching the proposed NRC limit of 350 mrem/year between 10,000 and 1,000,000 years. Figure 32 shows the same results, but scaled to the total energy generated by the waste in the repository. The dose per unit-energy-generated for the LIFE repository is lower than that of the Yucca Mountain base case, as expected, because a repository loaded with LIFE waste would represent a much larger amount of generated energy. The risk/benefit ratio of a "LIFE repository" is therefore lower. Note that most of the dose comes from ^{129}I, ^{135}Cs, and ^{242}Pu. Although the specific activity of ^{244}Pu is much higher in LIFE waste than in spent LWR fuel, the absolute amount of ^{244}Pu is small, and it does not appear that it will be a major contributor to dose. Similarly, the contribution to the dose from ^{93}Zr appears to be minor, owing to its relative immobility in the environment, and its small dose-conversion factor.

More refined calculations will need to be performed to check these preliminary results, particularly with respect to the simplifications made in treating Cm. Once information is available for the ^{14}C content of LIFE wastes, similar calculations will need to be done for the pre-10,000 year time period.

Mitigating the Threat of Proliferation

Comparison of TRU and Pu Produced by LIFE and LWR Fuel Cycles

LIFE will produce far less transuranic elements (TRU) and plutonium (Pu) for disposal than a comparable LWR. As shown in Table 3, the spent fission fuel from a DU-fueled LIFE engine will contain less than 1 kg of Pu per MT of initial heavy metal (assuming a burnup of 99% FIMA). In contrast, a typical LWR discharges approximately 10 kilograms of Pu per metric ton. Furthermore, on a unit of electrical energy basis, a LIFE Engine's more efficient use of fuel would generate less than 1 kg Pu (per GWe-net·yr), compared to about 250 kg for an LWR (lower portion of Table 3, and Figure 33a). The more complete burn that can be achieved with a LIFE engine, compared to an LWR, will also generate less TRU (including Pu) per plant (Table 3, and Figure 33b).

The smallest unit of LIFE fuel (a 2 cm-diameter pebble) is considered to be less attractive for theft than the smallest unit of LWR fuel (a rod, although in practice, it is difficult to remove a rod from an assembly). For example, at discharge, a representative LIFE pebble has a specific activity of approximately 21,000,000 Ci/kg-TRU, compared to a specific activity of approximately 23,000 Ci/kg-TRU for spent LWR fuel. Clearly, the LIFE fuel comes out of the engine very "hot", both thermally and radioactively. A single 2-cm pebble from a LIFE engine is a less attractive target for theft than a single LWR fuel rod (Figure 34). The LIFE pebble contains less TRU, and is much more radioactive.

Other Alternatives to Reduce Proliferation Risk

The comparison in the preceding section pertains to the proliferation risk from a conventional LWR and from a DU-fueled LIFE engine. LIFE engines can also be designed to use TRISO particles fabricated from LWR spent nuclear fuel, to remove that fuel as a target for diversion of actinides to weapon programs. The LIFE fuel fabrication process would not involve chemical partition of the LWR spent nuclear fuel. Only mechanical processes would be needed to fabricate the LIFE fuel. These SNF-burning LIFE engines would convert most of the actinides in that spent fuel (including the ^{238}U) to fission products.

Other critical and sub-critical systems have been proposed to fission the actinides in spent nuclear fuel. Table 7 compares these options with the LIFE engine. The two LIFE engines shown in the table have relatively low mass flow (~100 kg/TWe·hr) compared to most of the other options which have several hundred to thousands of kg//TWe·hr mass flow. The LIFE engines also result in a low amount of TRU (~0.5 wt %) compared to the other options which range from about 1 to 98 wt %. Thus, LIFE appears to be able to simultaneously burn the initial charge of uranium to near completion, while producing one of the smallest heavy-metal mass flows, and lowest concentrations of transuranic elements in the waste.

The only sub-critical system (other than LIFE) in the table is known as accelerator transmutation of waste (ATW), and it is used in three ways in Table 7 (rows 12, 15, and 16). In the ATW system, reprocessing is used to separate TRU from LWR SNF for burning in a lead-bismuthcooled reactor. In contrast, SNF can be burned in LIFE without significant isotopic enrichment or chemical reprocessing. The LIFE and ATW processes are compared in Table 7.

Repository Cost

The Need for Energy Drives the Nuclear Option

The worldwide energy consumption in 2003 was 421 quadrillion Btu (Quads), and included 162 quads of oil, 100 quads of coal, 99 quads of natural gas, 33 quads of renewable sources, and 27 quads of nuclear energy. The projected worldwide energy consumption for 2030 is 722 quads, corresponding to an increase of 71% over the consumption in 2003. The projected consumption for 2030 includes 239 quads of oil, 196 quads of coal, 190 quads of natural gas, 62 quads of renewable sources, and 35 quads of nuclear energy [EIA, 2006]. The current fleet of light water reactors (LRWs) provides about 20% of current U.S. electricity, and about 16% of current world electricity. The demand for electricity is expected to grow steeply in this century, well beyond the projections for 2030, as the developing world increases its standard of living. With the volatile pricing for oil and gasoline within the United States, as well as fear that CO_2 production from burning fossil fuels may be driving intolerable global warming, there is growing pressure to move away from oil, coal, and natural gas towards nuclear energy. Although there is a clear need for nuclear energy, issues facing waste disposal have not been adequately dealt with, either domestically or internationally. Better technological approaches, with better public acceptance, are needed.

Yucca Mountain Repository

The capacity of the first geological repository for high-level radioactive waste in the U.S. is statutorily limited to 70,000 metric tons (MT) of initial heavy metal equivalent by the Nuclear Waste Policy Act of 1982 as amended [Public Law 97-425]. The License Application for the Yucca Mountain repository allocates 63,000 MT of this capacity to the disposal of commercial spent nuclear fuel (CSNF), with the remaining 7,000 MT allocated to vitrified high-level radioactive waste (HLW glass) and DOE spent nuclear fuel (DSNF, including that from naval reactors). The ultimate physical capacity of a repository at Yucca Mountain could be higher (at least 120,000 MT and likely considerably higher) than the statutory limit. For simplicity in this report, we define a "Yucca Mountain Equivalent" (YME) repository as one that can accommodate the equivalent of 63,000 MT of heavy metal.

The most recent estimate of the total system life cycle cost for the Yucca Mountain Repository is $96 billion (in 2007$) to dispose of a total of 122,100 MT of waste, including 109,300 MT of CSNF [USDOE, 2008b]. It should be noted that this life-cycle cost is for waste volumes larger than the statutory limit. Comparing the 2007 estimate to the prior 2001 estimate, the cost per MT increased by about 10%, from $719 thousand to $788 thousand (both are 2007$). The cost increase is due to several factors, including the cost of temporarily storing the current inventory of spent nuclear fuel, as well as escalating costs for construction and procurement of materials for the engineered barrier system of the repository. Given the increasing cost for geological disposal and strong public and state governmental opposition, any nuclear power-generation option should be welcome if it can increase the quantity of electrical energy serviced by a facility such as Yucca Mountain, thereby decreasing the need for multiple repositories in the future.

The use of LIFE engines for the generation of electricity has significant benefits in terms of increasing the capacity and lifetime of a geologic nuclear waste repository, while simultaneously improving the societal risk/benefit ratio of such a facility. To frame this discussion, we have analyzed the volumetric, radiological, and thermal implications for the back end of the fuel cycle, for the case of a LIFE engine fueled initially with 40 MT of depleted uranium (DU), and operated continuously to burn-ups of 95%, 99%, and 99.5% FIMA (fissions per initial metal atom). Such an engine has a thermal output of approximately 2.9 GWt at steady state, and by the time the fuel reaches a burnup of 99% FIMA, the engine has generated in excess of 55 GWe-net·yr of electricity.

Conventional LWR Fuel Cycle Requires Many Repositories

The International Atomic Energy Agency (IAEA) has published the world wide inventory of reactors and spent nuclear fuel [Fukuda *et al.*, 2003]. These data are summarized in Table 8. The LWRs around the word have already generated enough spent nuclear fuel to fill 3.9 Yucca Mountain repositories. In North America alone, the inventory of spent fuel from current reactors, at the end of their power production, would fill 1.7 Yucca Mountain Equivalent repositories.

Comparing the End of the Fuel Cycle for LIFE & LWR Systems

LIFE engine development designs include hot-spot (HS) ignition fusion targets with a green laser (2ω) and chamber geometry similar to that used in the National Ignition Facility (NIF), as well as more advanced target types such as low incidence angle (LIA) fast ignition (FI) targets with either green or blue (3ω) lasers. Most work to date has assumed that the LIFE Engine would be sized to produce approximately one gigawatt of net electrical power (1 GWe). Most of the repository comparisons in this report are based upon this capacity. However, emerging systems and cost models at LLNL show that there is an economy of scale that leads to lower unit costs for larger plant size, and that larger plant size may be appropriate for the larger grid that will exist when the new plants are built. As the technology evolves, economic forces may drive more mature designs to plants capable of producing two gigawatts of electrical power (2 GWe) or greater. Similar scaling effects have been observed with other large power-production technologies. This economy of scale is illustrated in Figure 35.

As shown in Table 9, the nominal 1-GWe LIFE plant, which has a net electrical power output of 1.1 GWe, would require an initial fuel mass of 40 metric tons (MT) of natural or depleted uranium metal, and would operate (based on 90% availability) for 56 years. A larger 2.5 GWe plant would have a 66 MT fuel load, and would operate for 42 years. The uranium would be converted to uranium oxycarbide (UOC) and used to form the kernels at the core of enhanced TRISO particles (or other more advanced fuel forms) that are engineered to enable very high burnup. Several thousand TRISO particles will then be embedded in a larger pebble (2-cm diameter). Approximately 14 or 23 million of these pebbles would be required for the nominal 1-

GWe or 2.5-GWe LIFE plants, respectively. At end of life, the engines will have generated 54 and 92 GWe-yr of power, respectively. Both size engines would produce net electrical power at a rate of about 1.4 GWe-net·yr/MT. Once spent, and after a minimum 5-year cooling period (see earlier discussion of the thermal characteristics of spent LIFE fuel), the fuel pebbles would be loaded into standard-size transportation, aging and disposal (TAD) containers developed for the Yucca Mountain repository (the TAD material may be different for spent LIFE fuel). Assuming a 60% packing fraction of the pebbles in the TADs, the spent fission fuel from the 1- and 2.5-GWe LIFE engines would require 10.5 or 17.5 TADs, respectively (see earlier discussion of the volumetric characteristics of LIFE fuel). The TADs would ultimately be placed into waste packages similar to those developed for Yucca Mountain.

Although LIFE engines would be introduced into the market gradually, it is useful to make the direct comparison in Table 10 of the repository capacity required to service a hypothetical worldwide fleet of LIFE engines with a total electrical generating capacity equivalent to the current worldwide fleet of LWRs. The comparison in the last column of the table shows that use of a fleet of 1-GWe LIFE engines with the current worldwide LWR electrical generation capacity would reduce the current worldwide need for repository capacity from 3.9 YMEs to 0.2 YME. The $9B waste disposal cost for LIFE engines is $163B less than that of LWR waste.

In addition to the spent fission fuel, a complete accounting of the waste from a LIFE engine must also include other contaminated radioactive materials that require disposal as radioactive or hazardous waste or can be recycled for use in other LIFE engines. Because the mass of tungsten, steel, and beryllium is comparable to that of the spent fission fuel (Table 11), and because these materials are costly, a foundry for re-fabrication and recycle of these materials is required. Similarly, the hohlraum material from the fusion targets, and the fraction of the fusion-target tritium that is unburned, will be collected and recycled within the LIFE plant. It is anticipated that the non-fuel materials that are not recycled will qualify for shallow land burial as low- or intermediate-level radioactive waste.

As shown in Table 3 and Table 7, a LIFE engine will discharge approximately 20 times less spent fuel, 400 times less Pu, and 60 times less transuranic elements (TRUs) than comparable LWRs per unit electrical energy produced, assuming a once-through fuel cycle for the LWRs. The smaller quantities of spent fuel are due to the high burnup in LIFE, which uses the same fuel long enough to extract almost all the available fission energy in it. Therefore, it is expected that the repository capacity and disposal costs will be smaller than for conventional LWRs, as demonstrated in Table 8 and Table 10.

Chapter C. Gaps in Knowledge and System Vulnerabilities

Gaps in knowledge are listed below:

- Due to its mobility as gaseous $^{14}CO_2$ or dissolved carbonate species, ^{14}C in radioactive waste has the potential to contribute a major fraction of the radionuclide release and associated dose due to early failures of waste packages in a repository (Figure 29). The current burn calculations do not account for ^{14}C production because: 1) the most recent ENDF/B-VII cross section library does not allow for changes in the isotopic composition of carbon during a burn calculation, which "prevents" production of ^{14}C by neutron capture on ^{13}C; 2) all burn calculations to date have assumed that any oxygen in the fuel is entirely ^{16}O, thus not allowing for production by ^{17}O (n, α) ^{14}C; and 3) nitrogen impurities in the fuel, which will be present (*e.g.*, nitrogen is typically present in nuclear-grade graphite at the 50-150 ppm level), have not been accounted for in any burn calculations, thus eliminating the possibility of production by ^{14}N (n,p) ^{14}C. Future burn calculations will use older ENDF data, which do allow for a changing carbon isotopic composition; use actual oxygen isotopic composition, including the minor isotopes ^{17}O and ^{18}O; include nitrogen as an impurity in graphitic materials at reasonable levels. This will give us a first estimate of the ^{14}C production in LIFE engines. There will still be considerably uncertainty in the predicted values both because of the uncertainty in actual nitrogen levels, and because the cross section data for reactions involving ^{14}C as a target are old and scanty, thus predictions of the behavior of ^{14}C under conditions of an extended, intense neutron flux will be somewhat suspect.

- The current analysis is limited to waste arising from the extended burnup of a depleted uranium fuel. The isotopic composition of waste resulting from other fuels (*e.g.,* WG-Pu, HEU, Th, spent LWR fuel) needs to be established. One can expect that the composition of waste from fissile fuels will be quite different from that of fertile fuels, largely due to the much lower neutron fluence seen by the fissile fuels.

- The specific activity and radiotoxicity of LIFE waste is much higher than those of spent LWR fuel for the first few hundred years after discharge from the engine. The impact of this on shielding requirements for storage and transportation, and on the requirements for a surface handling facility at a repository need to be examined and documented. In part, the higher hazard of spent LIFE fuel should be compensated for by the much smaller quantities of material that need to be transported and handled, and the long lifetimes envisioned for LIFE engines.

- There are few data on the dissolution/leaching behavior of TRISO fuels, and there are no data relevant to the extremely high burnups intended for LIFE fuels. Indeed, the chemical and physical form of the fuel "kernel" in a solid LIFE fuel (either TRISO-based or of some other design) at the time of discharge is not known. The elemental composition of the fuel will be drastically different from the starting composition, and the phase relationships in that complex final mixture will need to be studied. The situation is further complicated by the high levels of radiation damage that the fuel will have experienced. At such high dpa, it is not clear that crystalline phases will form, or if formed, whether they will survive. The repository-relevant leaching and dissolution behavior of the fuel kernel material is therefore highly uncertain. Experiments will need to be conducted, first of surrogate unirradiated materials that have the appropriate chemical composition and phase assemblages predicted to be stable at the temperatures and pressures experienced by the fuel under operating conditions. Later experiments will need to be performed on fuels that have been irradiated to simulate the high doses expected for LIFE fuels. In addition, characterization of the corrosion rates of irradiated SiC (or whatever material is ultimately used as the “containment” material for LIFE fuel) should be conducted.

- Alternative designs for LIFE engines involve the use of a molten fluoride salt fuel (see relevant topical report in this series). The radionuclide inventories in waste from such a system should be similar to those of a solid fuel with the same initial isotopic composition, but the chemical and physical form of a wasteform for molten salt fuels is currently undefined. It is likely that two or more wasteforms will be needed: a metallic form and a multi-phase ceramic. If work is continued on molten salt fuel alternatives, then work to define wasteforms that are suitable for the waste streams resulting from the on-line and end-of-life processing of the salt will be needed. Although wasteforms have been developed for waste streams resulting from chloride salts [National Research Council, 2000], there has been no analogous work for fluoride salts. The aluminosilicate glass/ceramic wasteform developed for the chloride salt case is unlikely to work for the fluoride salts due to the incompatibility of fluoride with silicates. It will therefore be appropriate to examine alternative non-silicate host phases (e.g., phosphates, titanates, zirconates) for the radionuclides present in LIFE waste.

Chapter D. Strategy for Future Work

- Using the output of ongoing neutronics calculations, assess the isotopic composition, thermal, and radiological characteristics of fission waste from LIFE engines fueled with weapons-grade Pu, HEU, spent nuclear fuel, and Th.

- Using the output of ongoing neutronics calculations, estimate the range of ^{14}C concentrations that are likely to be present in spent LIFE fuel, and the impact of this inventory on the repository performance of LIFE waste.

- Using published data, conduct more detailed quantitative comparisons the quantities and characteristics of waste from LIFE engines *vs*. other proposed closed fuel cycles (*e.g.,* integral fast reactor fuel cycles) with respect to their repository requirements and their proliferation risks.

- Assess the impact of the higher thermal output of spent LIFE fuel and the higher radiation field (including a substantial neutron field due to ^{252}Cf) on interim storage and transportation requirements.

- In conjunction with the Transmutation & Phase Formation effort for LIFE, conduct experimental and modeling work to determine the phase assemblages likely to form in from the fission products in the high-burnup spent fuel from LIFE engines. Assess, and ultimately determine experimentally, the likely dissolution/leaching behavior of this material under repository conditions.
- Conduct more detailed assessments of the performance of a repository system loaded with LIFE waste, particularly with respect to the release and transport of the long-lived radionuclides in LIFE waste and the magnitude of the long-term doses attributable to releases from a repository.

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Burn and Radionuclide Inventory Calculations

Kevin Kramer, Jeff Latkowski, and Pihong Zhao

Thermal Calculations

Veraun Chipman

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TABLES

Table 1 - Physical characteristics of TRISO-based fuel. An alternative design has a 72 micron SiC middle shell, 958 micron TRISO particle diameter, 2730 TRISO particles per pebble, 2.9030 g U per pebble, 5.72 x 10^{-4} g SiC per TRISO particle, 13,778,638 pebbles per 40 MTU, and 9.371 waste packages per 40 MTU. The alternative design is used in the cost section of this volume.

Quantity	Value	Units
Spherical Pebble Radius	1	cm
Spherical Pebble Volume	4.189	cm^3
Total Uranium Loading in LIFE engine	40	tons
Spherical UCO Kernel Diameter	600	microns
Spherical UCO Kernel Volume	1.131E-04	cm^3
UCO Density	10.51	g/cm^3
Spherical UCO Kernel Mass	1.189E-03	grams
UCO Formula Mass (assuming atomic mass of natural U)	266.0394	g/mol
Spherical UCO Kernel - Equivalent U Metal Mass	1.064E-03	grams
Coating Porous Carbon Buffer Thickness	102	microns
Spherical Porous Carbon Buffer Volume	1.590E-04	cm^3
Porous Carbon Buffer Density	1.1	g/cm^3
Spherical Porous Carbon Buffer Mass	1.749E-04	grams
Coating Inner PyC Shell Thickness	5	microns
Spherical Inner PyC Shell Volume	1.028E-05	cm^3
IPyC Shell Density	1.95	g/cm^3
Spherical Inner PyC Shell Mass	2.005E-05	grams
Coating SiC Middle Shell Thickness	90	microns
Spherical SiC Middle Shell Volume	2.318E-04	cm^3
SiC Density	3.217	g/cm^3
Spherical SiC Middle Shell Mass	7.458E-04	grams
Outer TRISO Particle Diameter	994	microns
Outer TRISO Particle Volume	5.142E-04	cm^3
TRISO Particle Packing Density	0.3	
TRISO Particles per Pebble	2444	
Uranium Per TRISO Particle	1.064E-03	grams
Total Volume of All TRISO Particles in Pebble	1.2566	cm^3
Uranium Per Pebble	2.589	grams
PyC & Porous Carbon Per TRISO Particle	1.950E-04	grams
SiC Per TRISO Particle	7.458E-04	grams
Pebbles per LIFE Engine	15,391,073	Pebbles / 40 MTU
Waste Packages per LIFE Engine	10.47	WPs / 40 MTU

Table 1 – Cumulative thermal energy produced as a function of time and burnup in the LIFE engine (from file "case da0.xls")

% FIMA	Years in Engine	Cumulative Energy (GWt-d)
0	0	0
20	13.15	9.50E+03
40	25.64	1.87E+04
60	38.14	2.80E+04
80	50.63	3.72E+04
95	63.78	4.45E+04
99	70.36	4.67E+04
99.9	72.66	4.73E+04

Table 2 – Volumetric comparisons of spent LIFE and LWR fuels.

	Spent LIFE Fuel (99% FIMA)	**Average Spent LWR Fuel**
MTIHM per Yucca-Mountain-Style waste package	3.8	8.4
Average energy generated (GWt-day/MTIHM)	1168	38.5
Equivalent GWt-day per Yucca-Mountain-Style waste package	4438	325

1% FIMA ~= 9.6 GWt-day

Table 3 – Uranium and transuranic element content of LIFE fuel as a function of burnup.

	Grams element per MT of initial U at indicated burnup								
Element	**0%**	**20%**	**40%**	**60%**	**80%**	**95%**	**99%**	**99.90%**	**Average LWR fuel**
U	1.0E+06	6.4E+05	4.2E+05	2.4E+05	1.1E+05	2.4E+04	4.5E+03	2.1E+02	9.6E+05
Np	-	1.5E+03	1.3E+03	9.1E+02	4.7E+02	1.6E+02	3.9E+01	7.0E+00	6.8E+02
Pu	-	1.5E+05	1.6E+05	1.3E+05	6.9E+04	1.2E+04	7.2E+02	2.0E+01	9.9E+03
Am	-	5.2E+03	9.0E+03	1.0E+04	7.3E+03	1.8E+03	1.7E+02	4.4E+00	1.2E+03
Cm	-	3.6E+03	7.9E+03	1.3E+04	1.6E+04	1.1E+04	4.4E+03	1.0E+03	2.7E+01
Bk	-	-	1.7E+00	8.1E+00	2.1E+01	2.6E+01	1.6E+01	1.1E+00	-
Cf	-	-	1.3E+00	2.6E+01	5.4E+01	7.2E+01	1.0E+02	1.0E+01	-
Es	-	-	-	-	-	-	9.2E-01	4.3E-01	-
Total transuranics		1.6E+05	1.8E+05	1.6E+05	9.3E+04	2.5E+04	5.4E+03	1.1E+03	1.2E+04
	Grams element per GWe-year of energy generated at indicated burnup								
Element	**0%**	**20%**	**40%**	**60%**	**80%**	**95%**	**99%**	**99.90%**	**Average LWR fuel**
U	-	2.8E+06	9.4E+05	3.7E+05	1.2E+05	2.3E+04	4.1E+03	1.8E+02	2.4E+07
Np	-	6.6E+03	3.0E+03	1.4E+03	5.3E+02	1.5E+02	3.5E+01	6.2E+00	1.7E+04
Pu	-	6.6E+05	3.7E+05	2.0E+05	7.9E+04	1.1E+04	6.5E+02	1.8E+01	2.5E+05
Am	-	2.3E+04	2.0E+04	1.5E+04	8.3E+03	1.7E+03	1.6E+02	3.9E+00	3.0E+04
Cm	-	1.6E+04	1.8E+04	1.9E+04	1.8E+04	1.1E+04	4.0E+03	9.3E+02	6.9E+02
Bk	-		3.9E+00	1.2E+01	2.3E+01	2.5E+01	1.4E+01	1.0E+00	-
Cf	-		2.9E+00	3.9E+01	6.1E+01	6.8E+01	9.0E+01	9.1E+00	-
Es	-						8.4E-01	3.8E-01	-
Total transuranics		7.1E+05	4.1E+05	2.4E+05	1.1E+05	2.4E+04	4.9E+03	9.7E+02	3.0E+05

Table 4 – Nuclides contributing more than 4% to the total ingestion or inhalation radiotoxicity between 10^3 and 10^6 years of average spent LWR fuel and spent LIFE fuel with 99% FIMA.

Average Spent LWR Fuel	**Spent LIFE fuel (99% FIMA)**
^{241}Am	^{241}Am
	^{243}Am
	^{246}Cm
	^{248}Cm
	^{129}I
^{237}Np	
^{210}Pb	
^{210}Po	^{210}Po
^{239}Pu	^{239}Pu
^{240}Pu	^{240}Pu
^{242}Pu	^{242}Pu
^{225}Ra	
^{226}Ra	
^{229}Th	^{229}Th
^{230}Th	

Table 5 – Nuclides identified in the Yucca Mountain Total System Performance Assessment (TSPA) as dominating the doses for different time periods from a Yucca Mountain repository [Sandia, 2008].

	< 10,000 years	10,000 to 100,000 years	100,000 to 1,000,000 years
Most important radionuclides overall	^{99}Tc, ^{14}C, ^{129}I, ^{239}Pu	^{239}Pu, ^{129}I, ^{226}Ra	^{226}Ra, ^{242}Pu, ^{237}Np
Other nuclides important for specific scenarios	^{240}Pu, ^{241}Am	^{79}Se, ^{99}Tc, ^{135}Cs, ^{237}Np, ^{240}Pu, ^{242}Pu	^{79}Se, ^{99}Tc, ^{135}Cs, ^{237}Np, ^{240}Pu, ^{242}Pu

Table 6 – Activity ratios (Specific activity in 99% FIMA LIFE waste divided by specific activity in average LWR spent fuel) of nuclides of importance in the YMP TSPA for LA or that are present at significant levels in LIFE waste but were not considered in the YMP TSPA.

	Years since discharge							
Nuclide	**300**	**1,000**	**3,000**	**10,000**	**30,000**	**100,000**	**300,000**	**10^6**
C-14	a	a	a	a	a	a	a	a
Cl-36	a	a	a	a	a	a	a	a
Se-79	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Zr-93	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Tc-99	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Sn-126	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
I-129	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6
Cs-135	28.7	28.7	28.7	28.7	28.7	28.7	28.7	28.7
Ra-226	-	0.0	0.0	0.1	0.1	0.1	0.1	0.1
Ac-227	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Th-229	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Th-230	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
Pa-231	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U-233	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1
U-234	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1
U-235	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U-236	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Np-237	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
U-238	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0.0	0.0	0.1	0.1	0.1	0.1	0.3	high
Pu-240	0.4	0.4	0.4	0.4	0.4	0.5	high	high
Pu-242	0.6	1.0	2.0	4.0	5.0	5.1	5.1	5.1
Pu-244	b	b	b	b	b	b	b	b
Cm-246	8.1×10^3	8.1×10^3	8.1×10^3	8.1×10^3	8.1×10^3	8.1×10^3	8.1×10^3	8.1×10^3
Cm-248	b	b	b	b	b	b	b	b

[a]No data available for LIFE case. Existing burn calculations for LIFE do not include estimates of ^{14}C and ^{36}Cl production.
[b]Nuclide not present at significant levels in YMP inventory

Table 7 – Comparison of the heavy-metal mass flows and fuel compositions for LIFE engines and other advanced fuel cycles [Nuclear Energy Agency, 2006]. The LIFE values are derived from neutronics models, and the mass flow is an upper bound that does not include the energy generated during the startup and incineration phases of the LIFE plant operation. These assumptions are slightly different than those used to generate the energy-normalized entries in Table 3.

Reactor and Fuel Cycle		HM mass flow	Fuel Composition After Irradiation (Wt.% of Initial HM)					
		kg/TWe·hr	U	Np	Pu	Am	Cm	Total TRU
1	**LIFE 1-GWe DU fuel (99% FIMA)**	93	0.45	0.004	0.07	0.02	0.44	**0.54**
2	**LIFE 2-GWe DU fuel (99% FIMA)**	91	0.45	0.004	0.07	0.02	0.44	**0.54**
3	**Once-through PWR (60 GWt-day/MTHM)**	2050	98.5	0.10	1.35	0.08	0.01	**1.54**
4	**PWR w/ Pu burning in MOX (1-pass reprocessing)**	225	91.5	0.02	7.24	0.68	0.16	**8.10**
5	**PWR w/ Pu+Np burning in MOX (1-pass reprocessing)**	215	90.4	0.42	8.35	0.71	0.14	**9.62**
6	**PWR w/ Pu burning in EU-MOX (multi-pass reprocessing)**	575	89.5	0.05	9.32	0.89	0.22	**10.48**
7	**PWR w/ Pu+Am burning in EU-MOX (multi-pass reprocessing)**	238	91.3	0.06	7.74	0.71	0.18	**8.69**
8	**PWR w/ Pu+Am burning in EU-MOX (multi-pass reprocessing)**	711	92.7	0.09	6.05	0.84	0.34	**7.32**
9	**DUPIC cycle (1-pass reprocessing + burning of spent PWR fuel in CANDU reactors)**	1997	99	0.06	0.87	0.04	0.01	**0.98**
10	**European FR (fully closed cycle)**	890	77.6	0.12	21.12	0.88	0.2	**22.32**
11	**PWR + Am, Pu, (Cm) burning in FR (multi-pass reprocessing)**	390	78.6	0.07	20.71	0.55	0.05	**21.38**
12	**Double Strata System: PWR+FR+Accelerator transmutation (fully closed cycle)**	106	57.1	0.06	39.81	2.56	0.51	**42.94**
13	**PWR+IFR (fully closed cycle)**	289	69.8	0.65	26.6	2	0.98	**30.23**
14	**Gen IV gas-cooled IFR (fully closed cycle)**	849	79.3	0.15	19.48	0.87	0.24	**20.74**
15	**Accelerator-driven transmutation of minor actinides**	46	5.4	6.09	47.58	23.15	17.72	**94.54**
16	**Accelerator-driven transmutation of TRU**	117	1.9	3.29	73.48	12.37	8.96	**98.10**

Table 8 – Worldwide base of installed LWRs showing generating capacity and inventory of spent fuel (at end of life).

	LWRs	LWR Generating Capacity	Total SNF in storage	Yucca Mtn. Equivs. (YMEs) Needed	Cost for YMEs
	#	GWe	kT HM	#	U.S. $B
Western Europe	146	126	72	1.1	51
Eastern Europe	67	46	34	0.5	24
N. America	124	112	105	1.7	74
Asia & Africa	104	75	33	0.5	23
World	**441**	**359**	**244**	**3.9**	**172**

Note: The cost estimates for YME repositories are based on the latest available unit cost (k$/MT) for Yucca Mountain. One YME is assumed to have the capacity to accept 63 thousand metric tons of heavy metal (kT HM). Its costs are scaled to the latest Yucca Mountain cost estimate of 80.4% (CSNF cost share) of $96.18B (YM cost, in 2007$), for the 109.3 thousand metric tons CSNF in that estimate).

Table 9 – Design parameters of two LIFE plants using LIA-FI targets with green lasers, and with depleted uranium blankets using 958 micron diameter TRISO particles. Costs are preliminary, with some subsystem costs not fully developed.

	1 GWe Engine	>2 GWe Engine	
Net Electrical Power	1086	2460	MWe
Fission Fuel Loading	40.0	66.4	MTHM
Burnup	99	99	% FIMA
Burn Duration	50.0	37.5	Full Power Years
Pebbles per Engine	13.8	22.9	Millions of pebbles
Pebbles per Waste Package	1.47	1.47	Millions of pebbles
Waste Packages per Engine	9.4	15.6	
Plant availability	90	90	Percent
Plant Lifetime	55.6	41.7	Years
Thermal Energy Generated	52,800	87,700	GWt·d
Net Electrical Energy	54.3	92.2	GWe-net·yr
Power per MT Fuel	1.36	1.39	GWe-net·yr/MT
Cost of Electrical Power	1	0.66	Normalized

Note: The last five rows of the table are based on the time at design power, and do not include the times for startup and incineration, and the power produced during those times. These assumptions are slightly different than those used to generate the energy-normalized entries in Table 3.

Table 10 – Repositories required at the end of LIFE fleet life, had the existing LWR fleet been a hypothetical fleet of 1-GWe LIFE engines (which have similar operating periods to LWRs with extended licenses). Compare with the current worldwide situation shown in Table 8.

	LIFE Engines	LIFE Generating Capacity	LIFE Total SNF	LIFE YMEs Needed	Cost for LIFE YMEs	Repository Cost Differential LWR-LIFE
	#	GWe	kT HM	#	U.S. $B	U.S. $B
Western Europe	116	126	5	0.07	3	48
Eastern Europe	42	46	2	0.03	1	23
N. America	103	112	4	0.06	3	71
Asia & Africa	69	75	3	0.04	2	21
World	**330**	**359**	**13**	**0.21**	**9**	**163**

Note: The LIFE engine net electrical power for this estimate is 1.086 GWe. Cost estimates for LIFE repositories are based on the unit cost (k$/MTIHM) for Yucca Mountain. The LIFE repository unit cost may be somewhat higher than shown because LIFE waste requires about twice as many waste packages per MTIHM as LWR waste.

Table 11 – Other spent materials from the LIFE fuel cycle. It is assumed that fusion target materials will be recycled within the LIFE power plant. Replacement first walls are included in the quantities.

	LWR	LIFE			
	Spent Fission Fuel	**Spent Fission Fuel**	**Spent First Wall Tungsten**	**Spent ODS Steel**	**Spent Be Multiplier**
	kT HM	**kT HM**	**kT**	**kT**	**kT**
Western Europe	72	5	1.4	3.8	2.2
Eastern Europe	34	2	0.5	1.4	0.8
N. America	105	4	1.2	3.4	2.0
Asia & Africa	33	3	0.8	2.3	1.3
World	**244**	**13**	**4**	**11**	**6**

Note: The LIFE engines also include a neutron reflector and FLiBe coolant that are exposed to neutron flux. LWRs include the pressure vessel, internal components, and water coolant that are exposed to neutron flux.

Figures

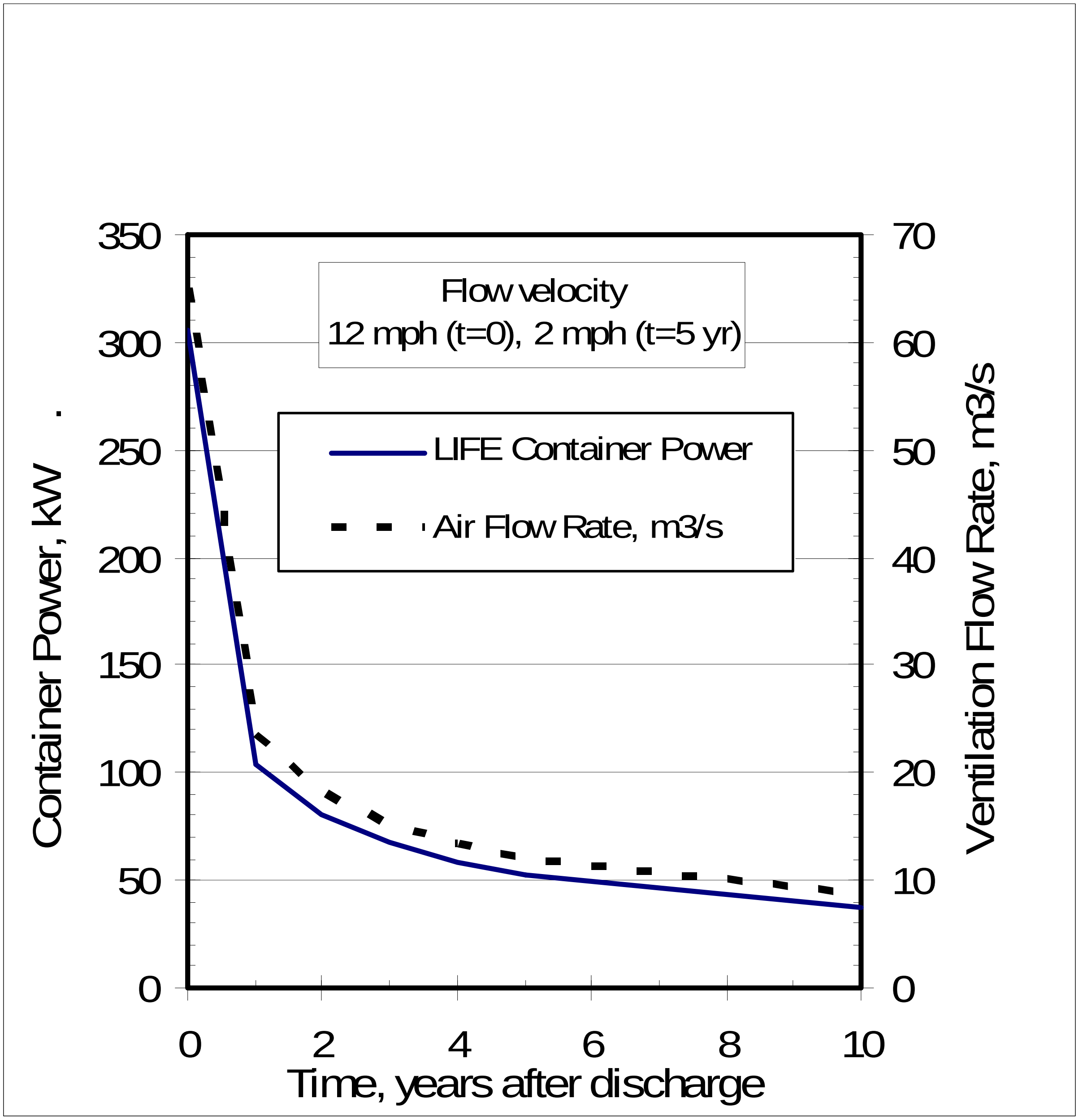


Figure 1 – The container power and ventilation rate for interim storage of LIFE spent nuclear fuel with a static heat transfer fluid.

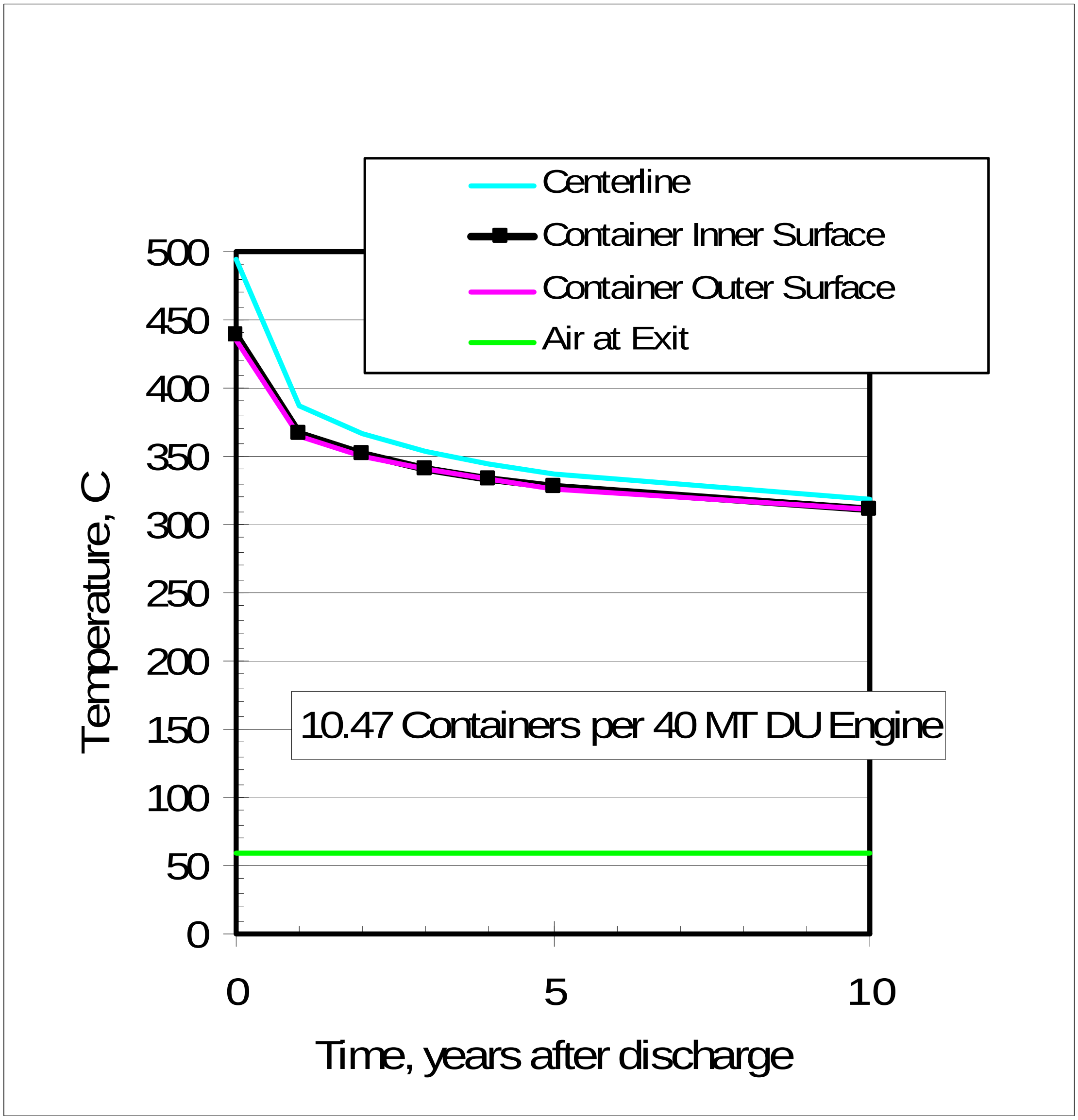


Figure 2 – Temperatures at the container centerline, fuel:container interface, container surface, and air exit.

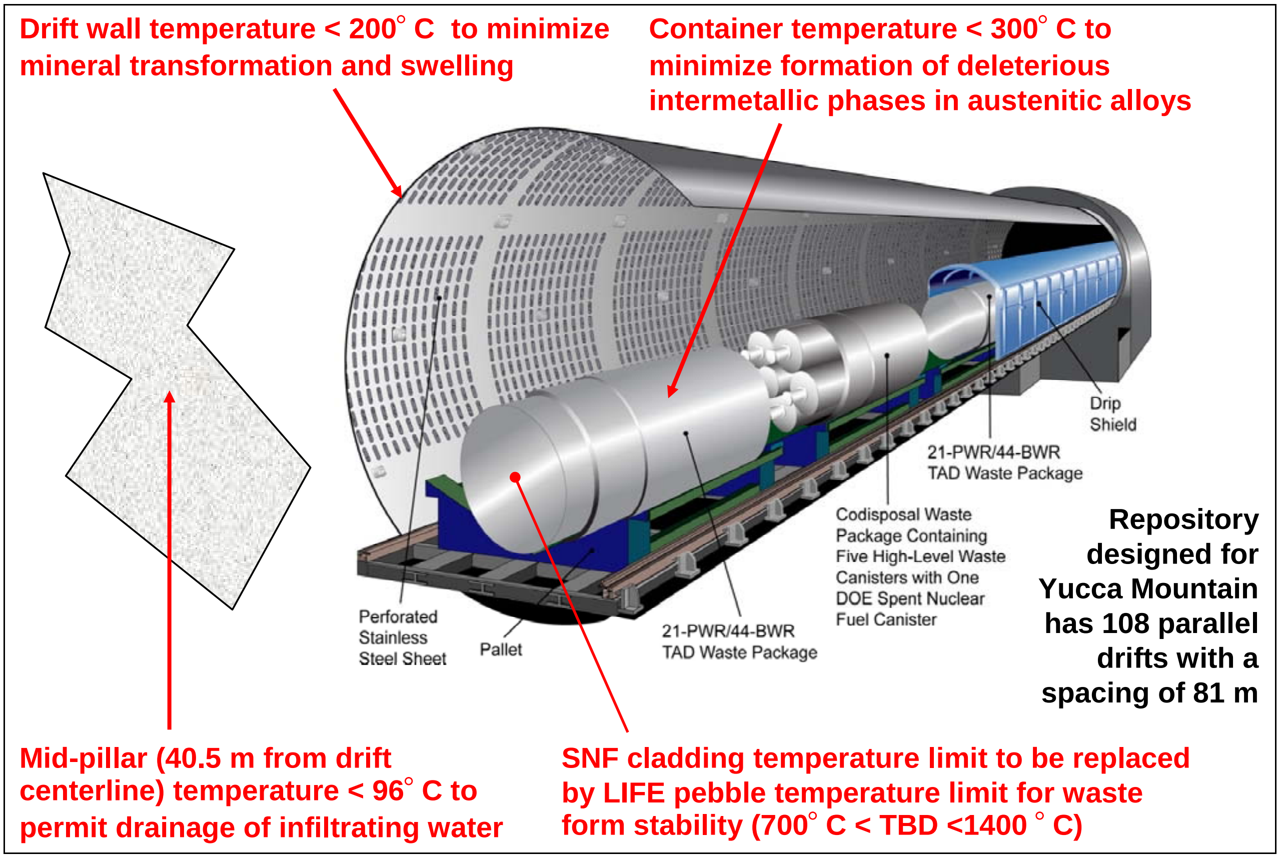


Figure 3 – The Yucca Mountain repository design and thermal constraints.

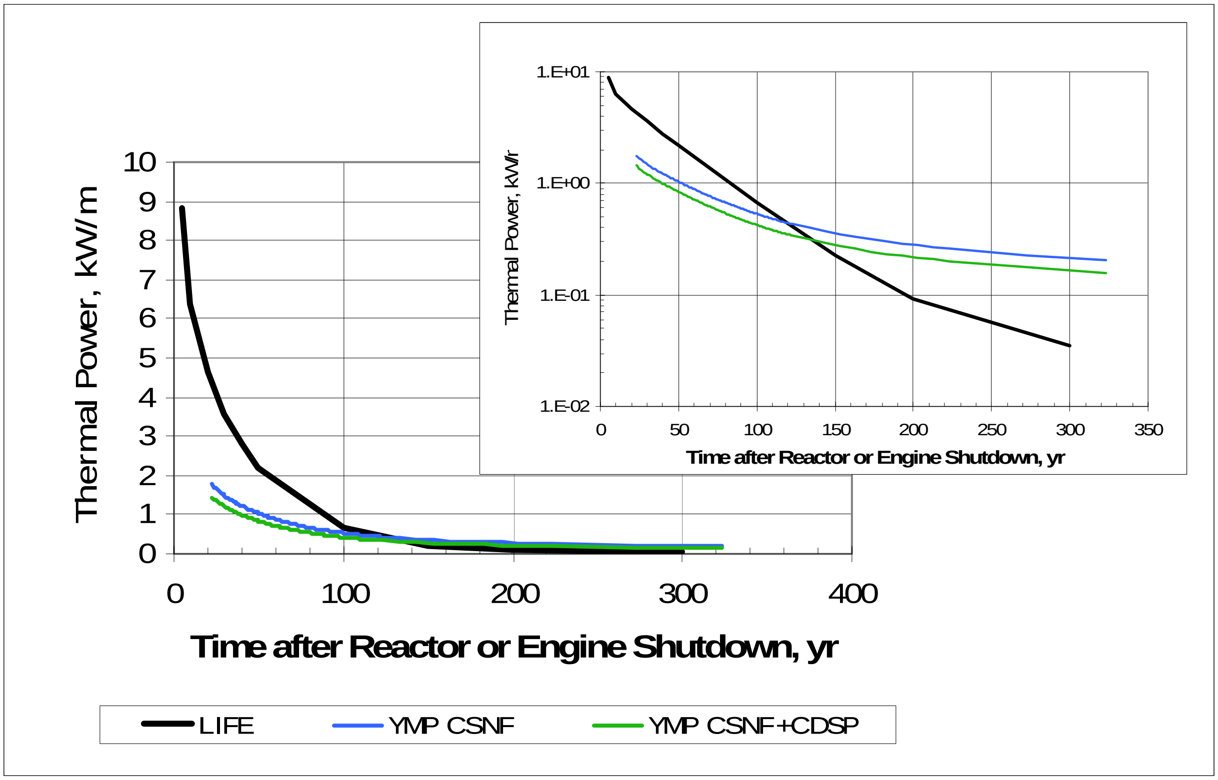


Figure 4 – Thermal power histories for spent LIFE fuel and Yucca Mountain waste. The calculation is based on 40 MT DU, 99% FIMA, and 10.47 WPs/LIFE Engine.

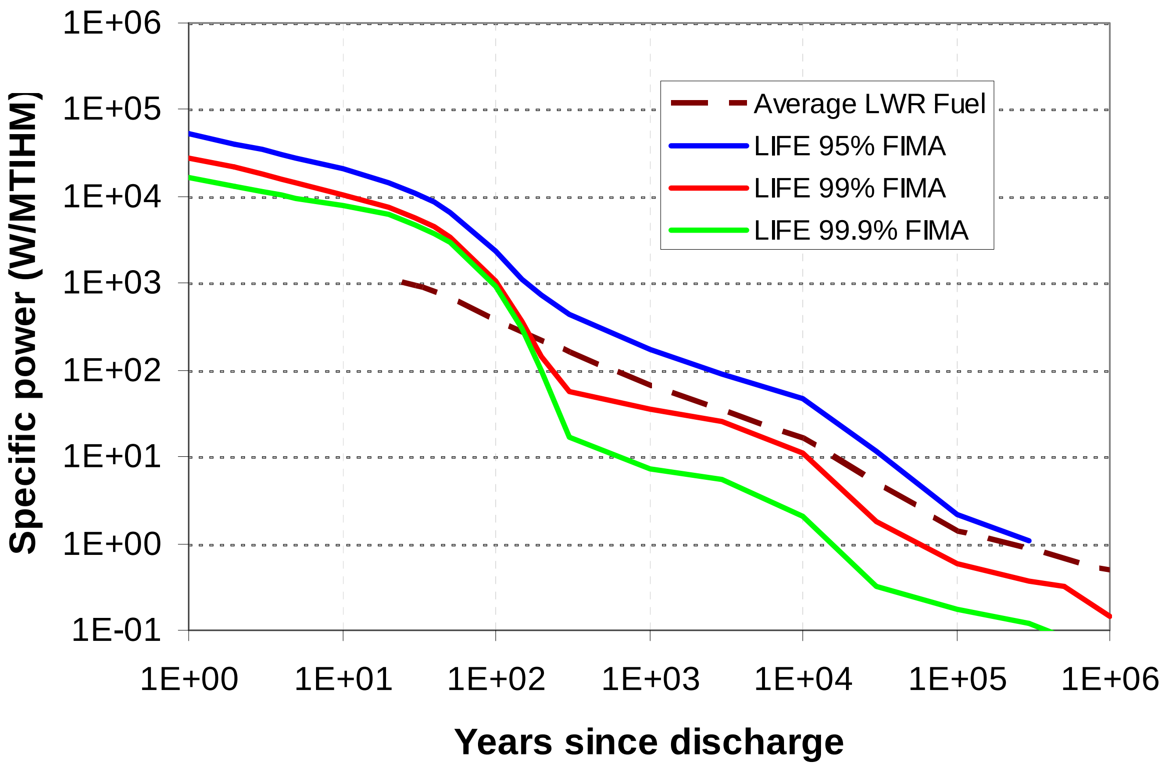


Figure 5 – The thermal power of spent fission fuel from LIFE Engines compared with spent LWR fuel, as a function of time. Three potential burn-up conditions are shown for the LIFE fuel, corresponding to 95%, 99% and 99.9% FIMA. After a few hundred years, the thermal power of both LWR fuel and LIFE fuel is dominated by the decay of the actinides. The differences in the thermal powers of LIFE fuels with different burnups are a reflection of the decreasing actinide content of the fuel as burnup increases.

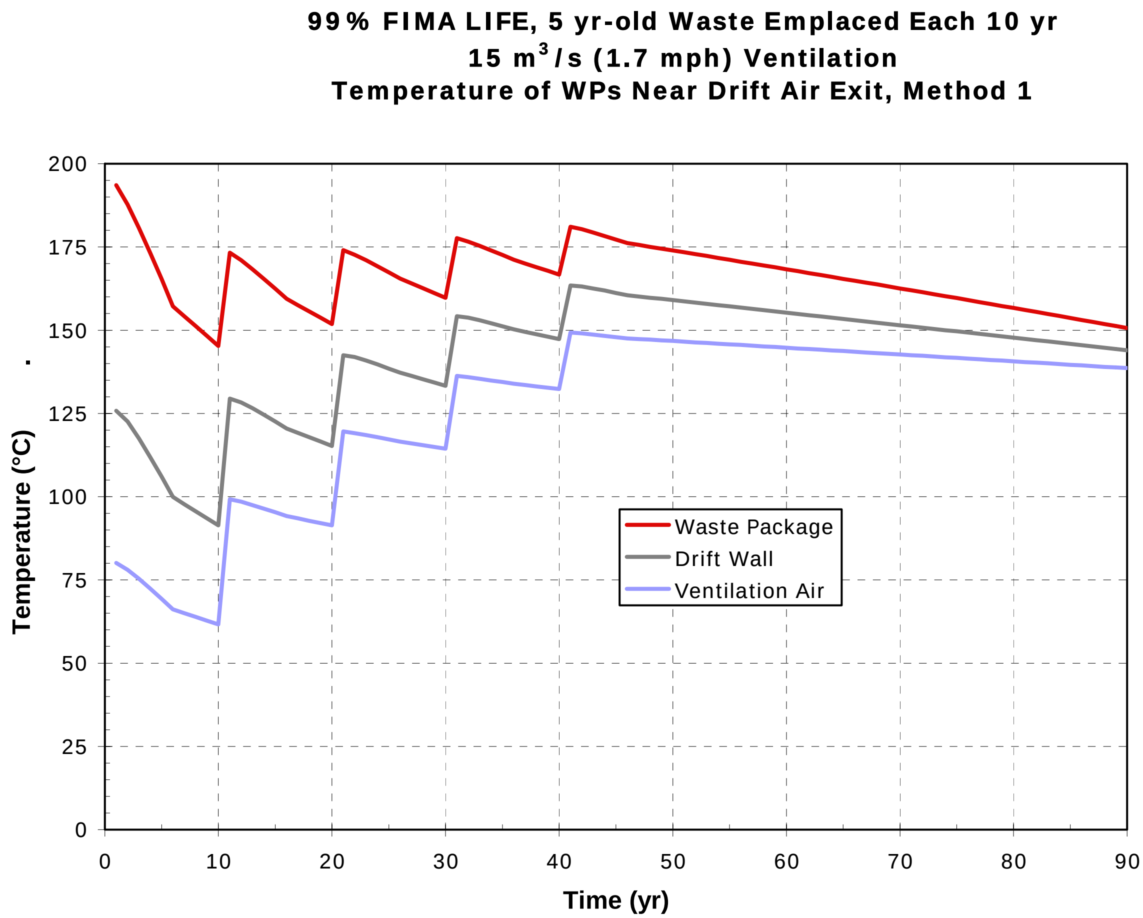


Figure 6 – Waste package, drift wall, and ventilation air temperature histories for the Variation 1 calculation method. The domain is a 625-meter long drift loaded every 10 years in five 125-meter long sections and then ventilated for an additional 50 years. Each 125-meter long section was calculated with eight equally sized well-mixed volume elements. At the start of each emplacement decade, the rock domain temperature and air inlet temperature for each section were reset to the previous decade's ending value at the section end (because the previous decade's result also represents the current decade for the section just upstream).

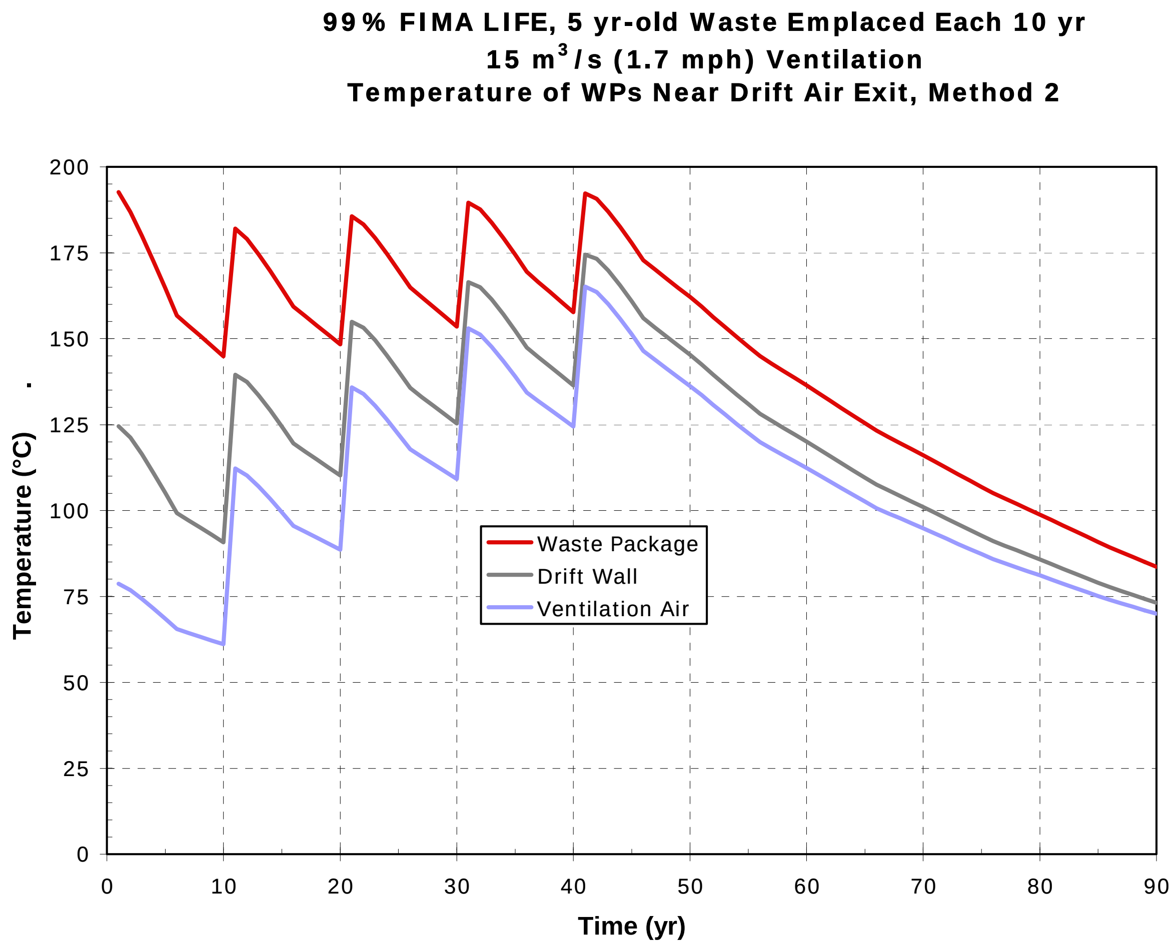


Figure 7 – Waste package, drift wall, and ventilation air temperature histories for the Variation 2 calculation method. The domain is a 625-meter long drift loaded every 10 years in five 125-meter long sections. This variation did not subdivide the five emplacement sections. However, the loss of spatial resolution in the method allowed more realistic use of initial and boundary conditions, with no resetting of rock domain temperatures or approximation of air temperatures at the interface between sections.

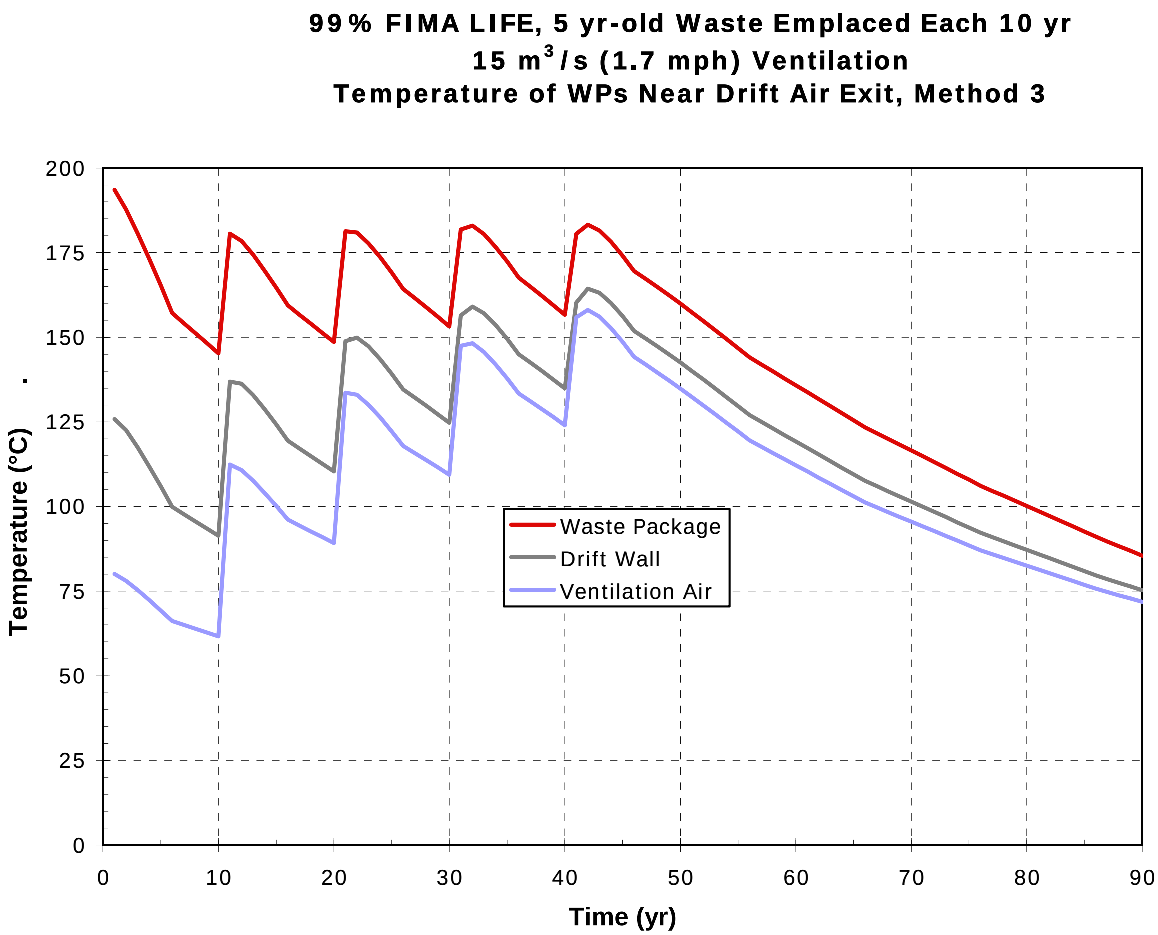


Figure 8 – Waste package, drift wall, and ventilation air temperature histories for the Variation 3 calculation method. The domain is a 625-meter long drift loaded every 10 years in five 125-meter long sections and then ventilated for an additional 50 years. Each 125-meter long section was calculated with eight equally sized well-mixed volume elements. At the start of each decade, the rock domain temperature was reset to ambient. The air inlet temperature for each year of a decade was taken from the section exit temperature for the same year in the previous decade (because the previous decade's result also represents the current decade for the section just upstream).

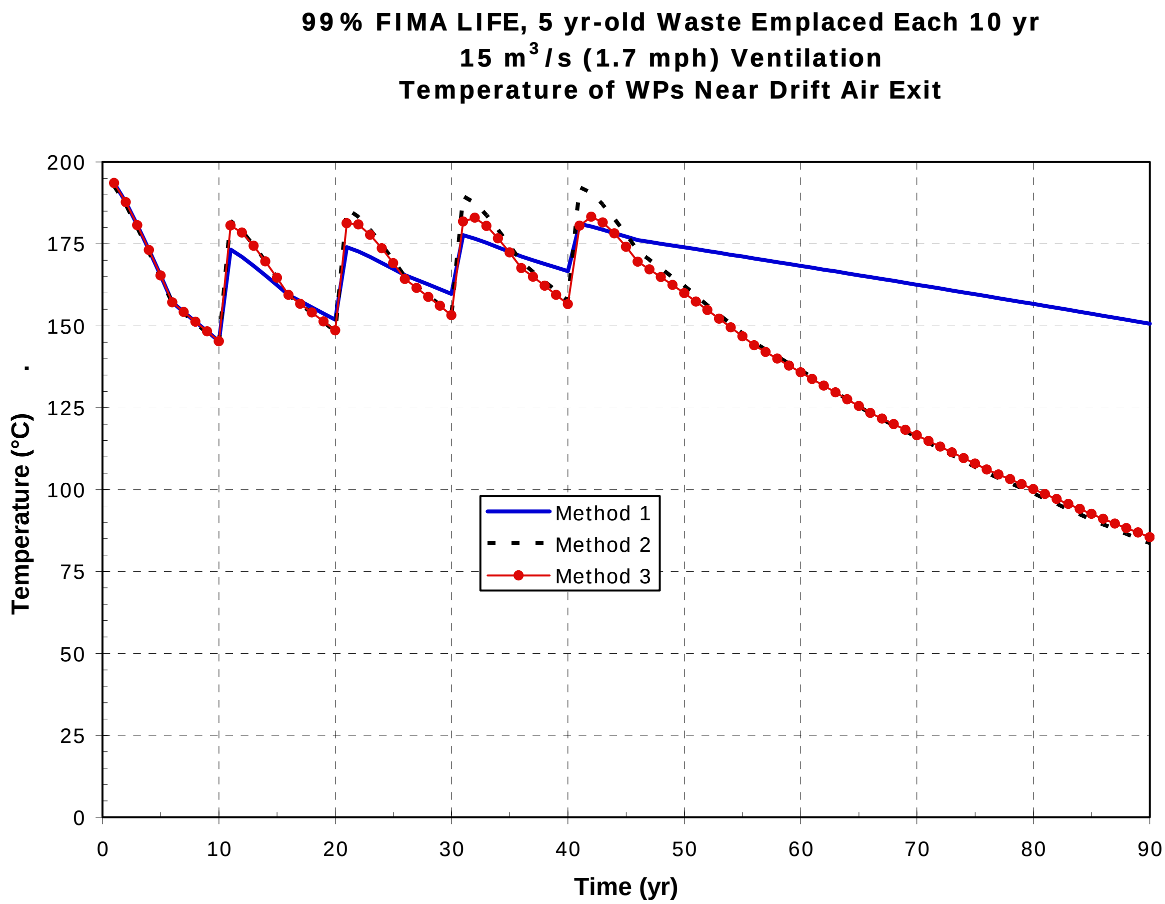


Figure 9 – Comparison of waste package temperature histories at the drift end (air exit end), for the three calculation methods (variations).

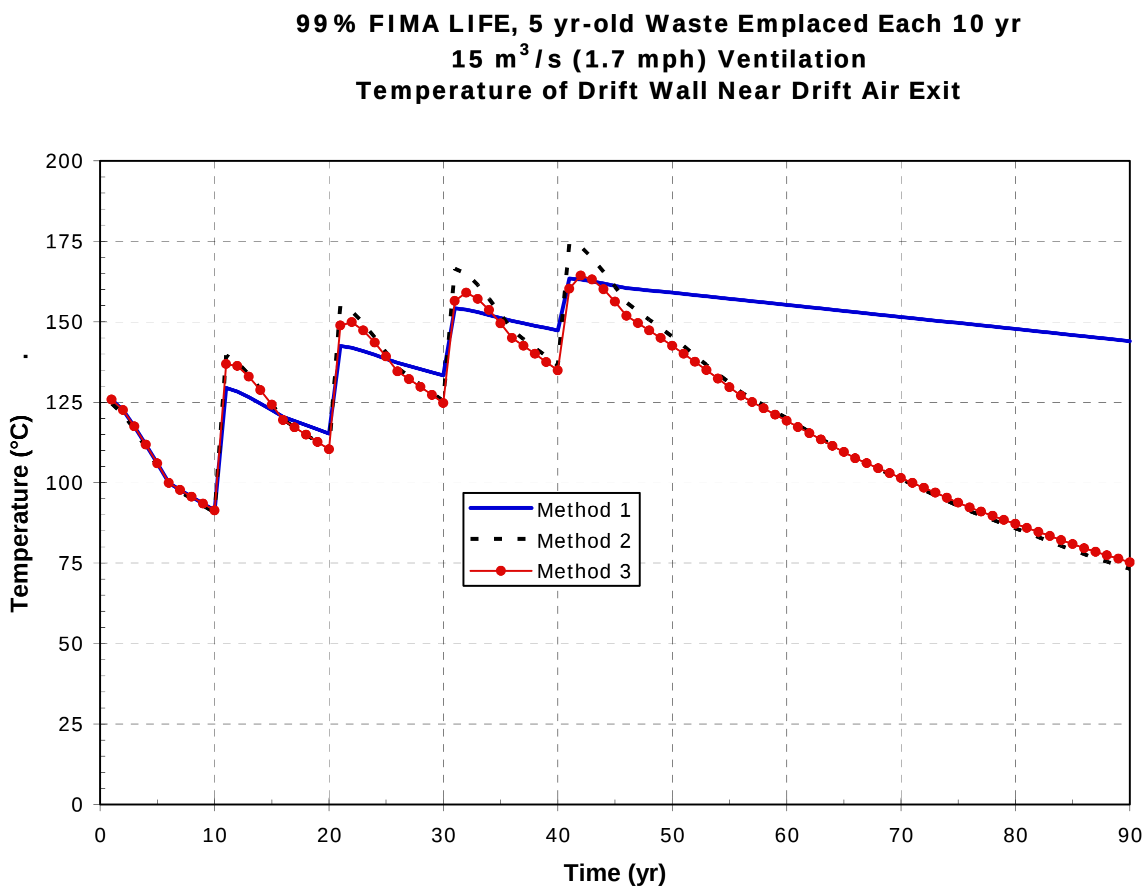


Figure 10 – Comparison of drift wall temperature histories at the drift end (air exit end), for the three calculation methods (variations).

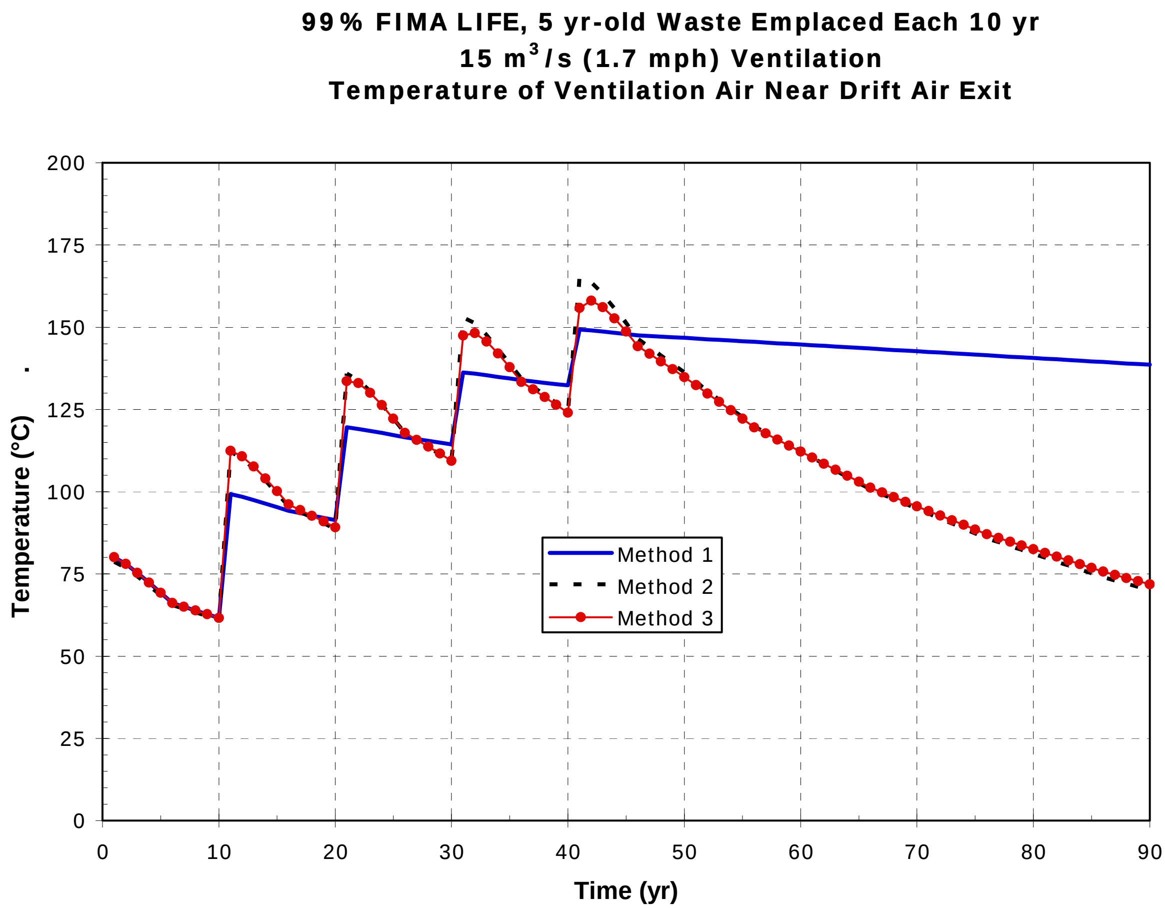


Figure 11 – Comparison of ventilation air temperature histories at the drift end (air exit end), for the three calculation methods (variations).

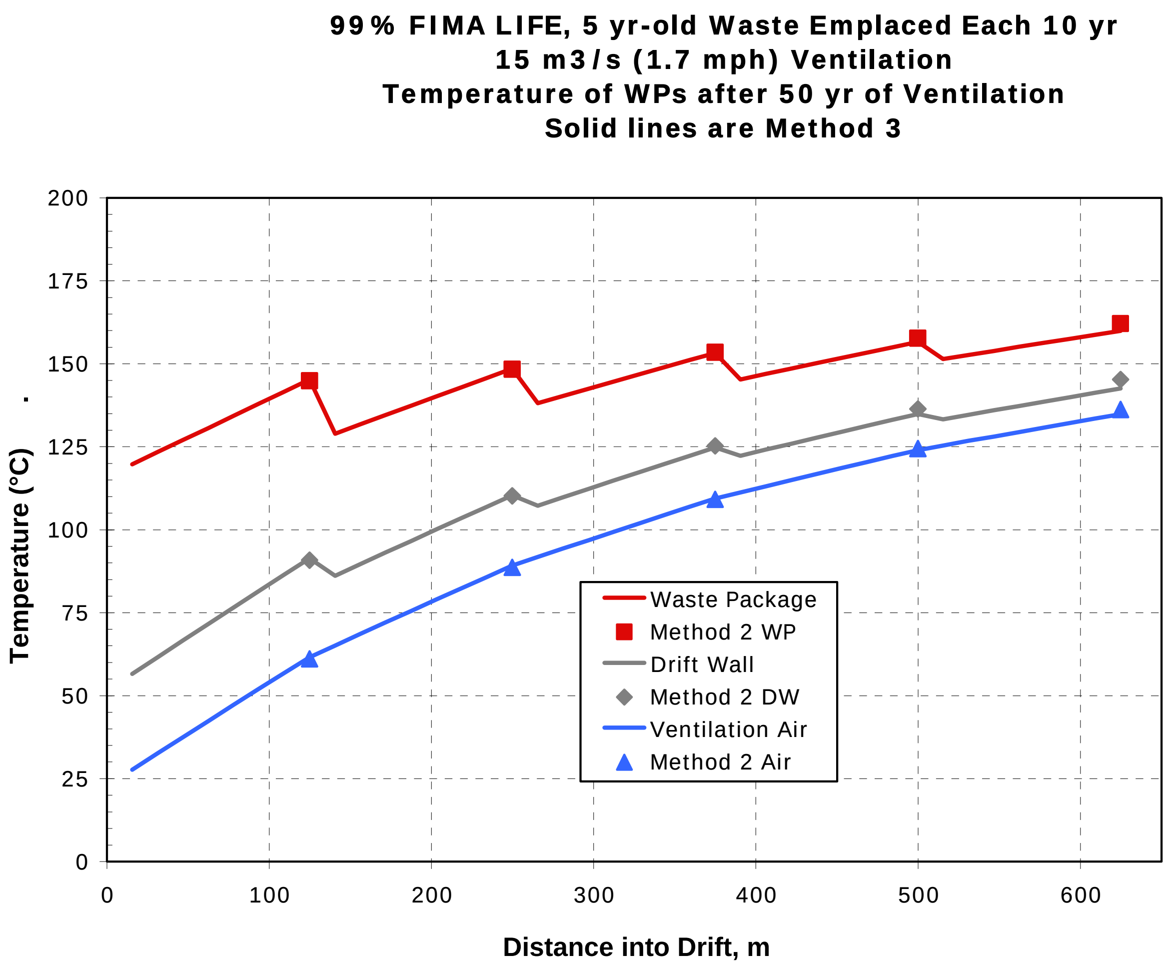


Figure 12 – Waste package, drift wall, and ventilation air temperatures, at 50 years after start of emplacement, as a function of distance into the drift, in the airflow direction, for Variation 3, for a 625-meter long drift loaded every 10 years in five 125-meter long sections and then ventilated for an additional 40 years. For comparison, the results of Variation 2 are also shown, at the five locations for which temperatures were calculated (the end of each emplacement section).

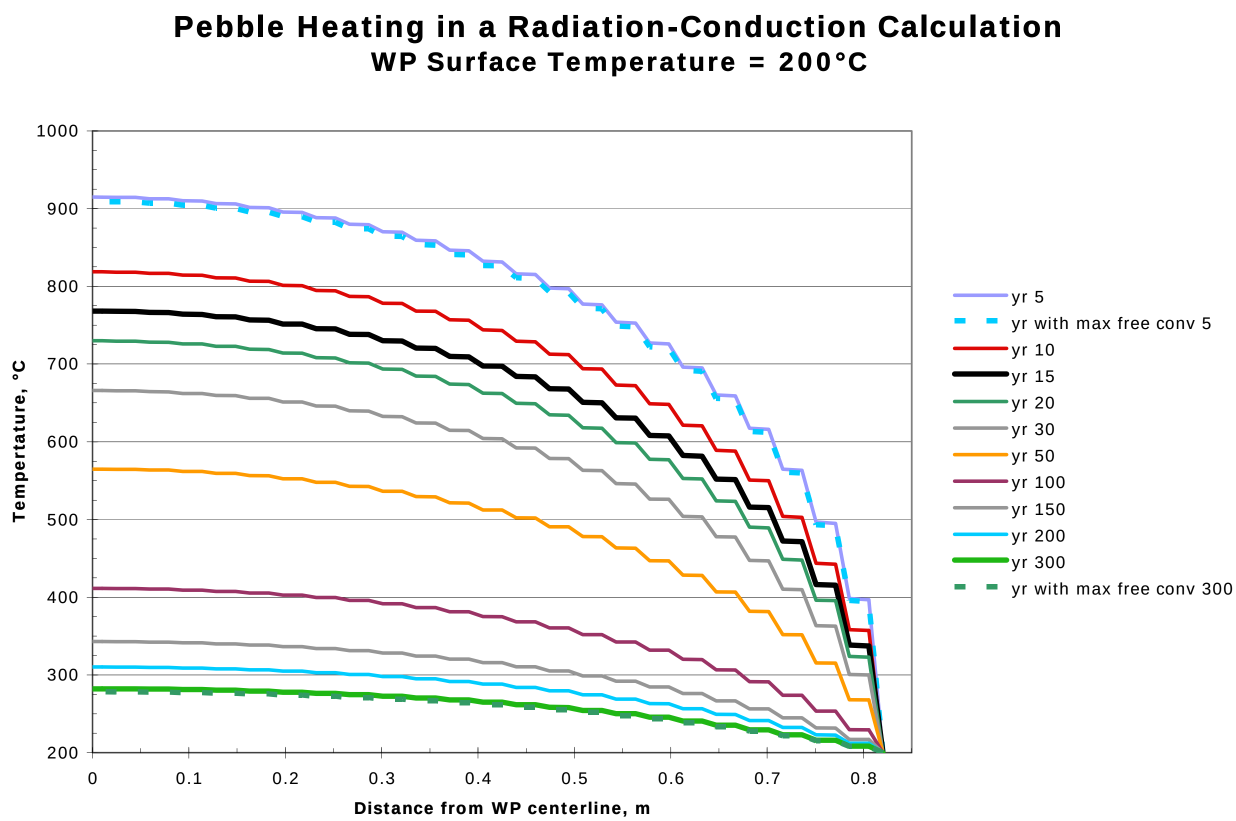


Figure 13 – Temperature of the interior of a LIFE waste package for normal operations during the preclosure period.

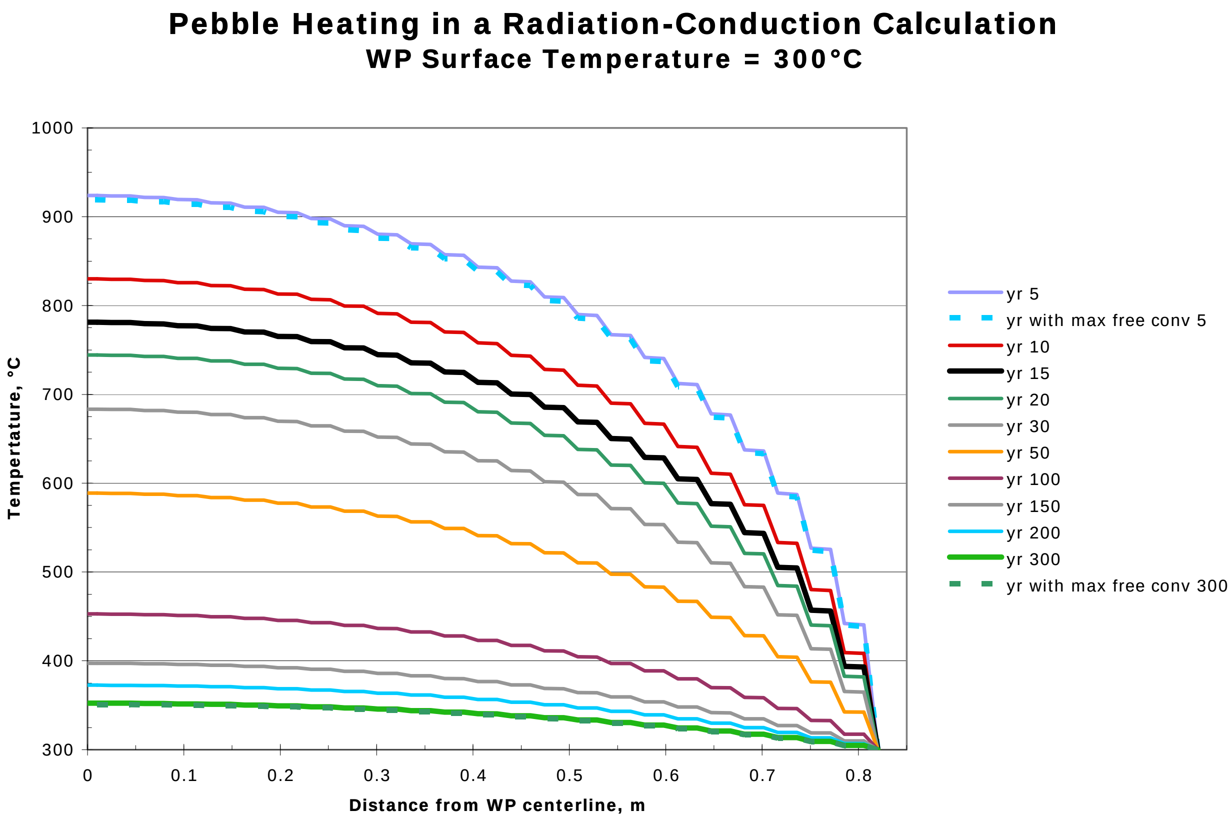


Figure 14 – Temperature of the interior of a LIFE waste package for off-normal operations during the preclosure period.

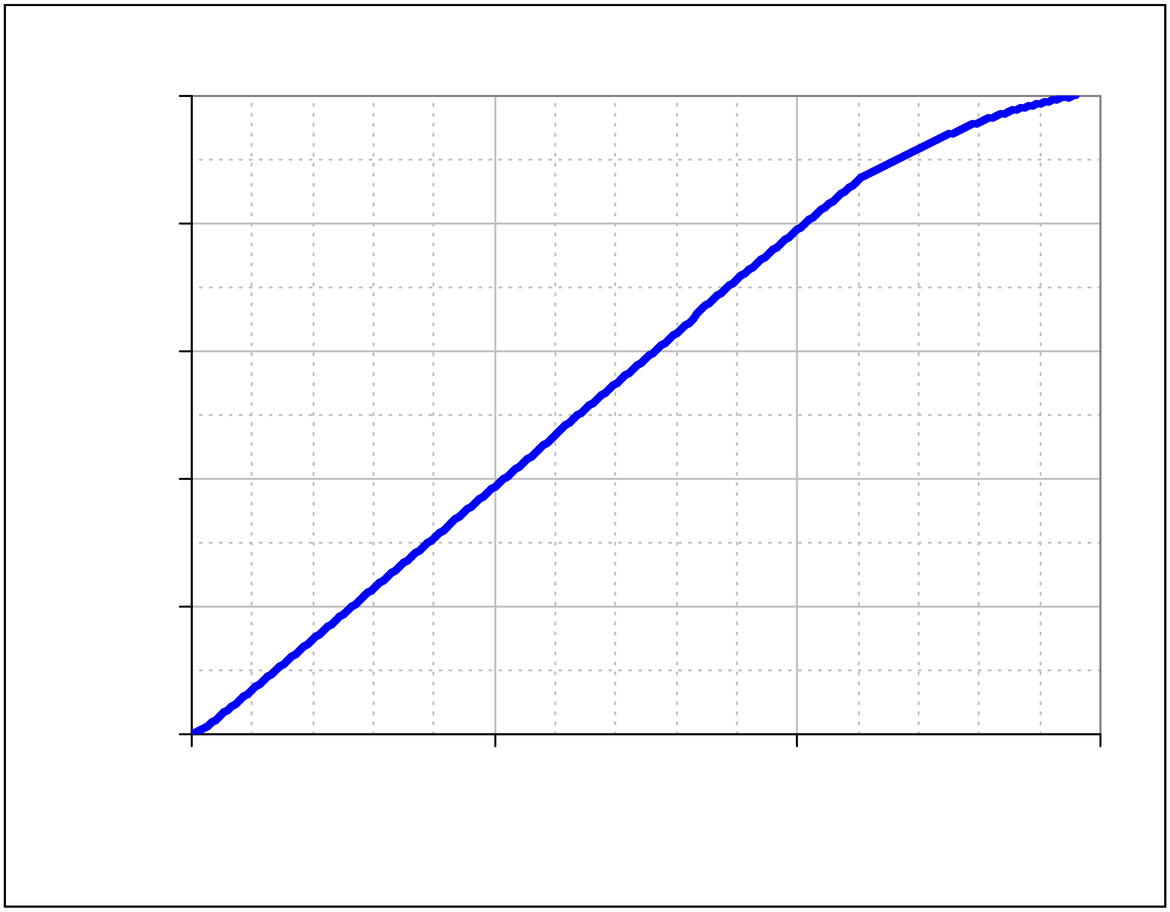


Figure 15 – Burnup (expressed as fissions per initial metal atom, FIMA) *versus* time for the base case for LIFE used in this report (from file “case da0.xls”)

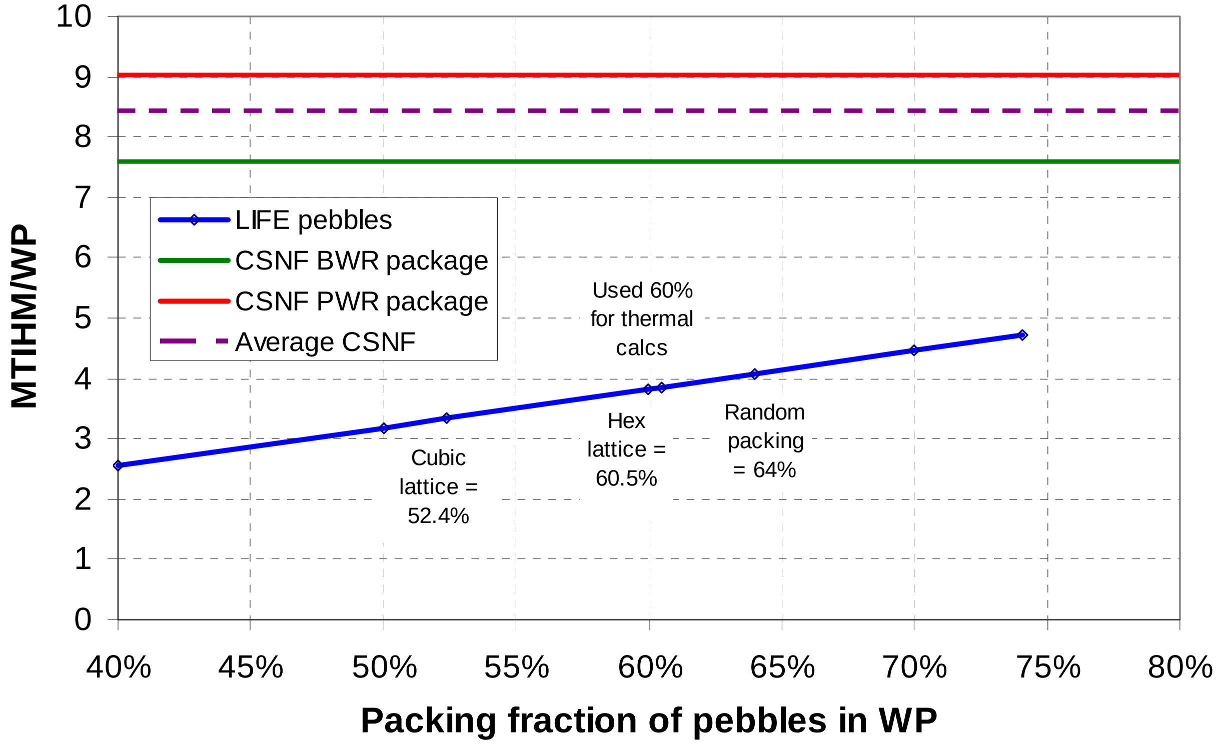


Figure 16 – Plot showing the mass loading of heavy metal in waste packages as a function of packing fraction of TRISO fuel pebbles and CSNF in Yucca-Mountain-style waste packages. A packing fraction of 60% was used for thermal calculations. The heavy metal density in LIFE waste packages containing TRISO pebbles would be somewhat less than half that of packages containing CSNF.

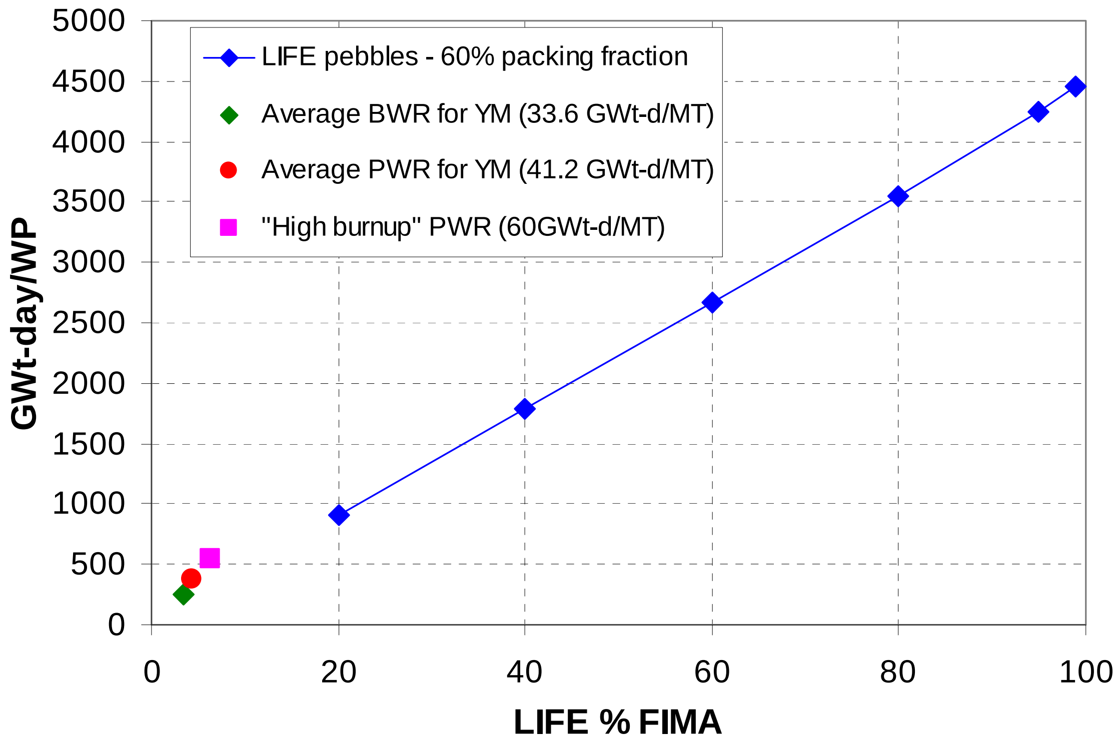
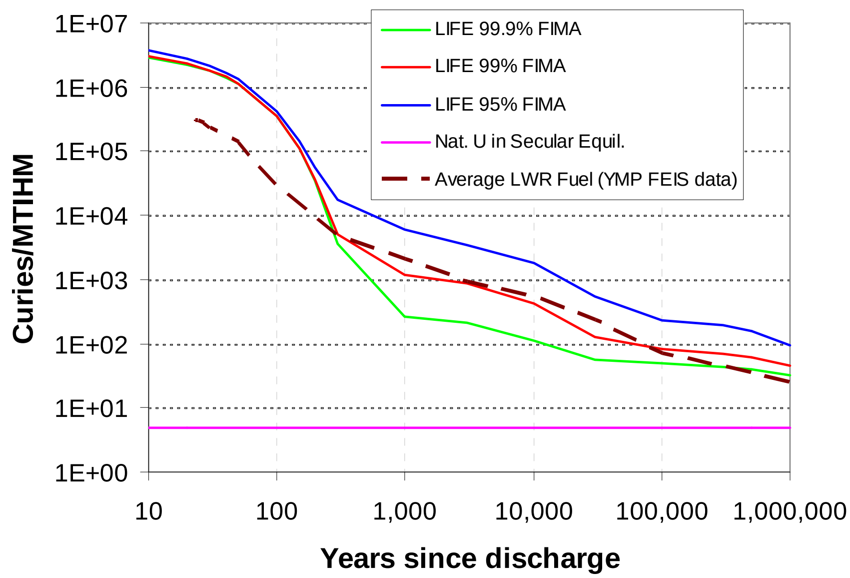


Figure 17 – Plot comparing the energy produced by the amount of CSNF or LIFE waste per waste package for Yucca-Mountain-Style packages. Each package of LIFE waste represents much more generated energy.



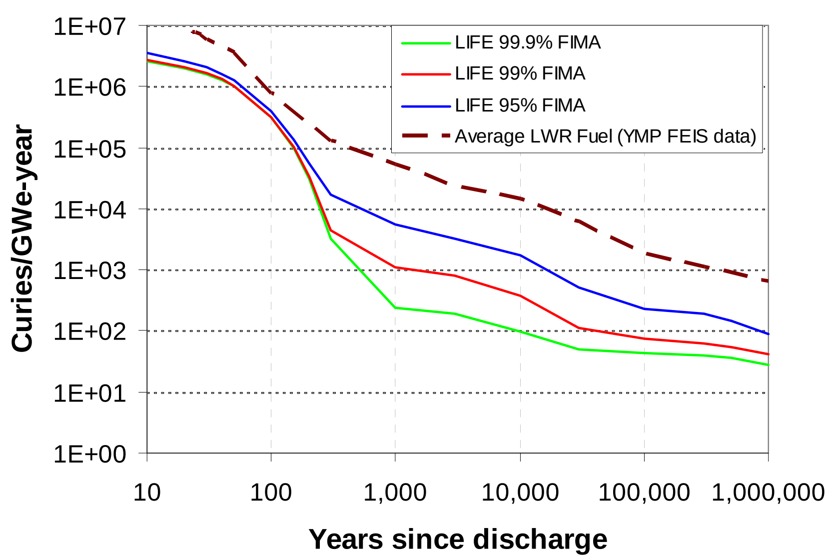


Figure 18 – (a) Comparison of the specific activity of spent LIFE fuel as a function of time since discharge with that of average LWR fuel. For comparison, the specific activity of natural uranium in secular equilibrium with its daughter products is also plotted. (b) Activity of spent LIFE fuel normalized to the total energy generated by that fuel. For comparison, the similarly normalized activity of average LWR fuel is also plotted.

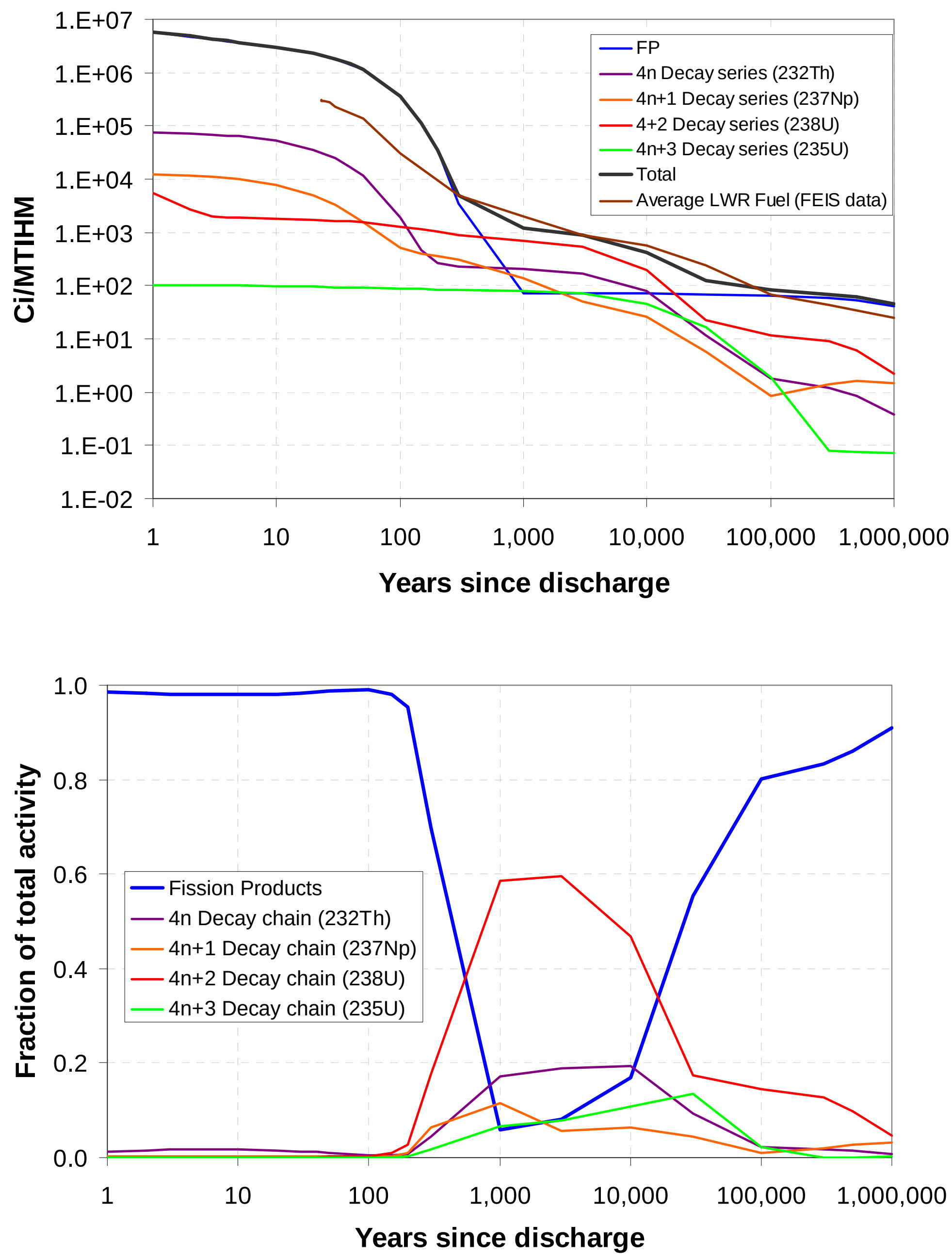
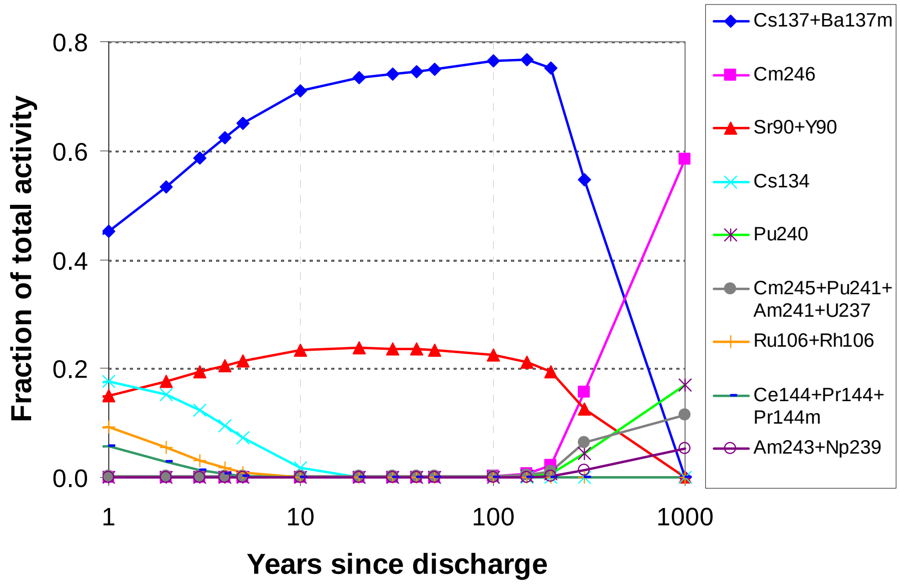


Figure 19 – (a) Contributions of fission products and actinides (plus daughters) to the specific activity of spent LIFE fuel (99% FIMA, other burnups are similar) as a function of time. Fission product activity dominates at early and very late times. The actinide decay chains dominate at intermediate times. (b) Fractional activity of spent LIFE fuel (99% FIMA, other burnups are similar) as a function of time showing the contributions of fission products and the four actinide decay series to the total activity.



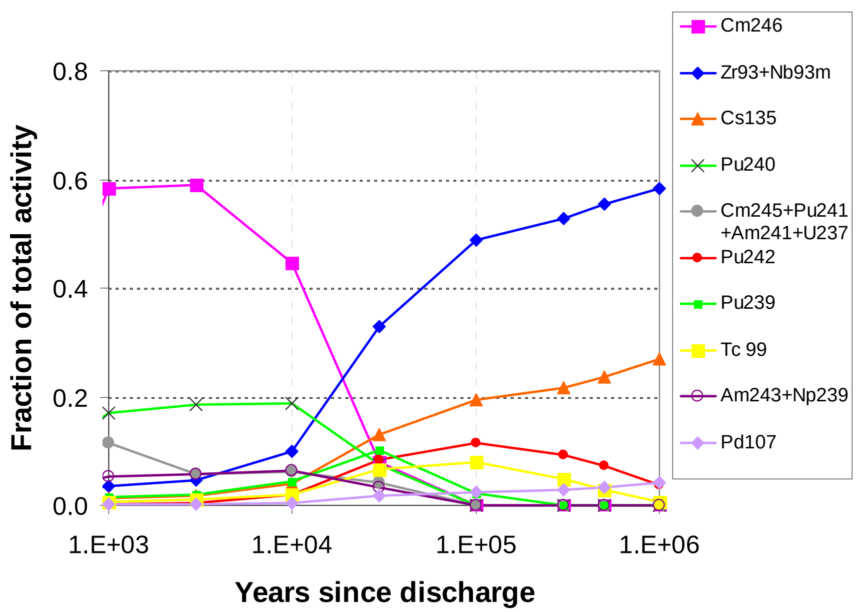


Figure 20 – (a) Fractional contribution of individual nuclides and decay chains in secular equilibrium to the total activity of 99% FIMA LIFE fuel for the period 1 to 1000 years post discharge. Figure includes all nuclides (or decay chains) that contribute more than 5% to the total activity at any time during this period. (b) Fractional contribution of individual nuclides (or decay chains in secular equilibrium) to the total activity of 99% FIMA LIFE fuel for the period 1000 to 1,000,000 years post discharge. Figure includes all nuclides (or chains) that contribute more than 5% to the total activity at any time during this period.

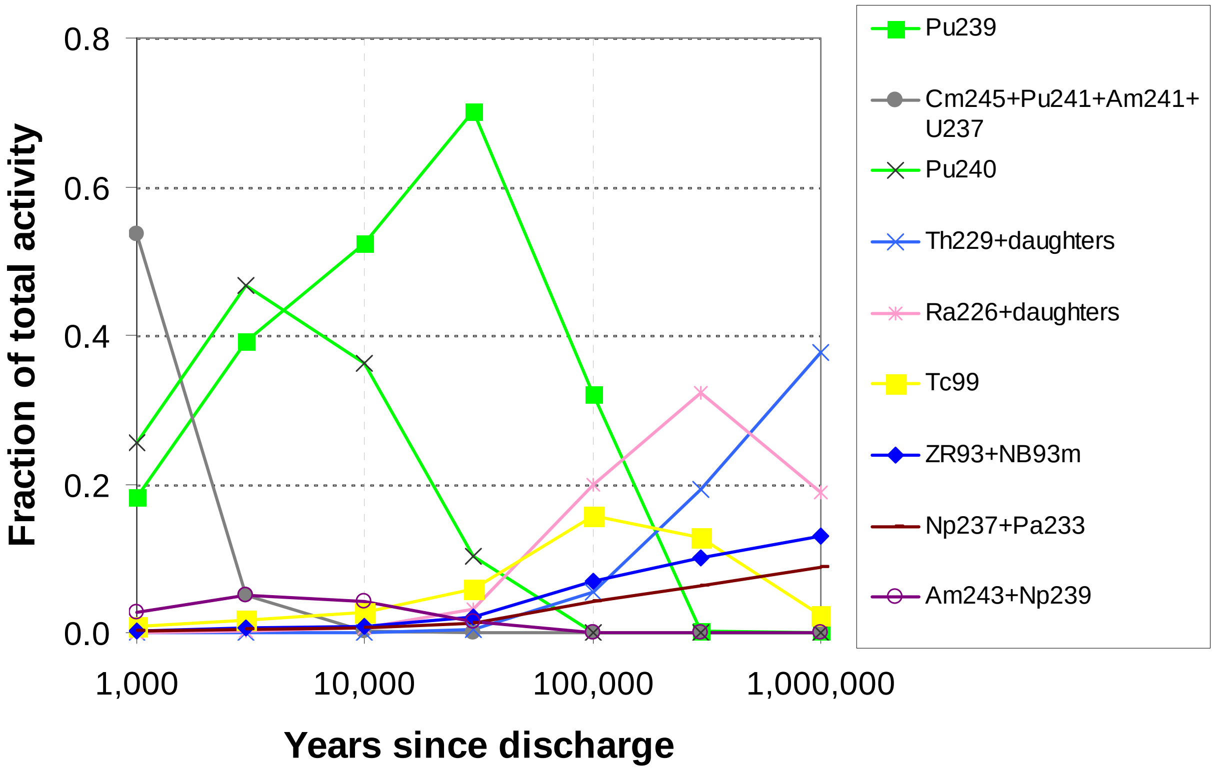


Figure 21 – Fractional contribution of individual nuclides (or decay chains in secular equilibrium) to the total activity of average spent LWR fuel for the period 1000 to 1,000,000 years post discharge. Figure includes all nuclides (or chains) that contribute more than 5% to the total activity at any time during this period.

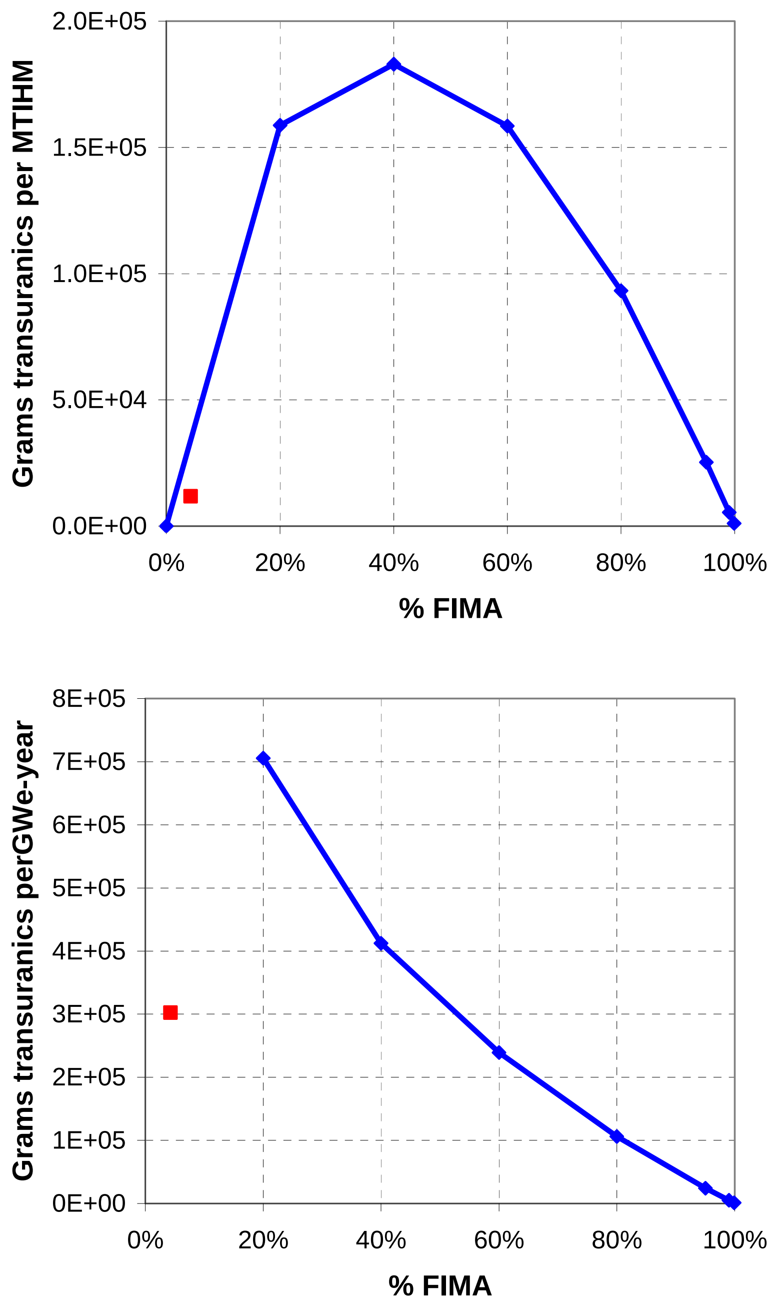
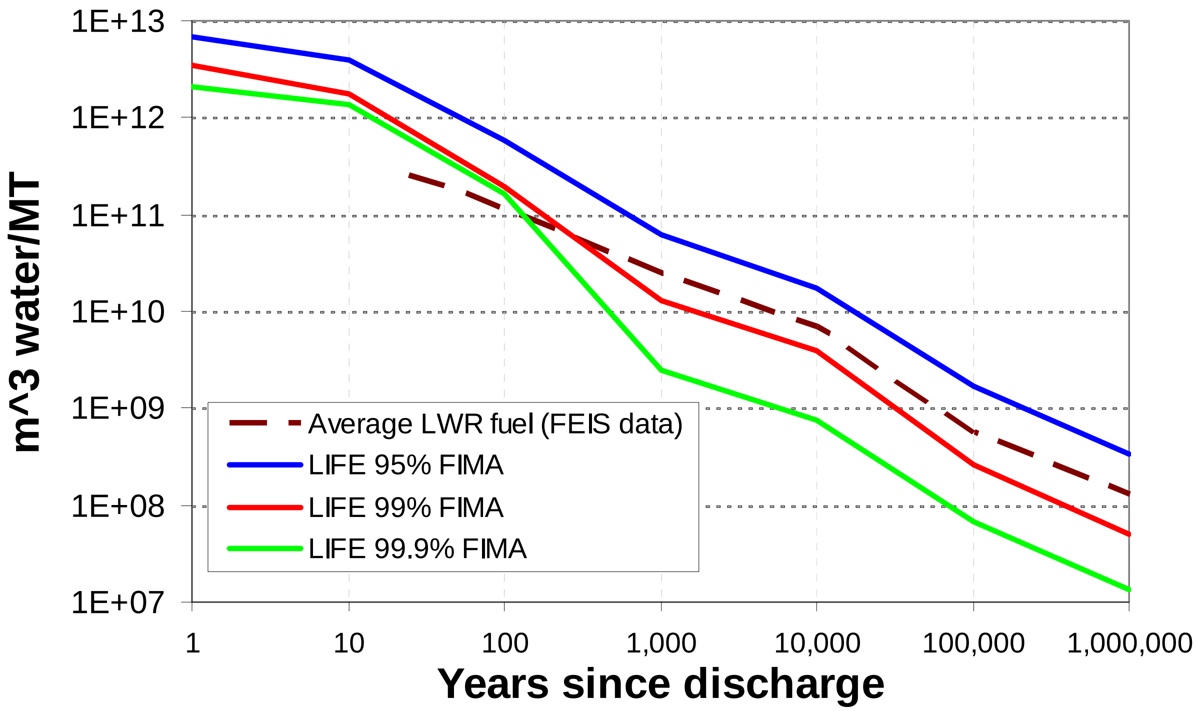


Figure 22 – Transuranic (TRU) elements in spent LIFE fuel (blue line) and average CSNF (red square). (a) Grams of TRU per metric ton of initial heavy metal; (b) Grams of TRU per GWe-year of power generated.



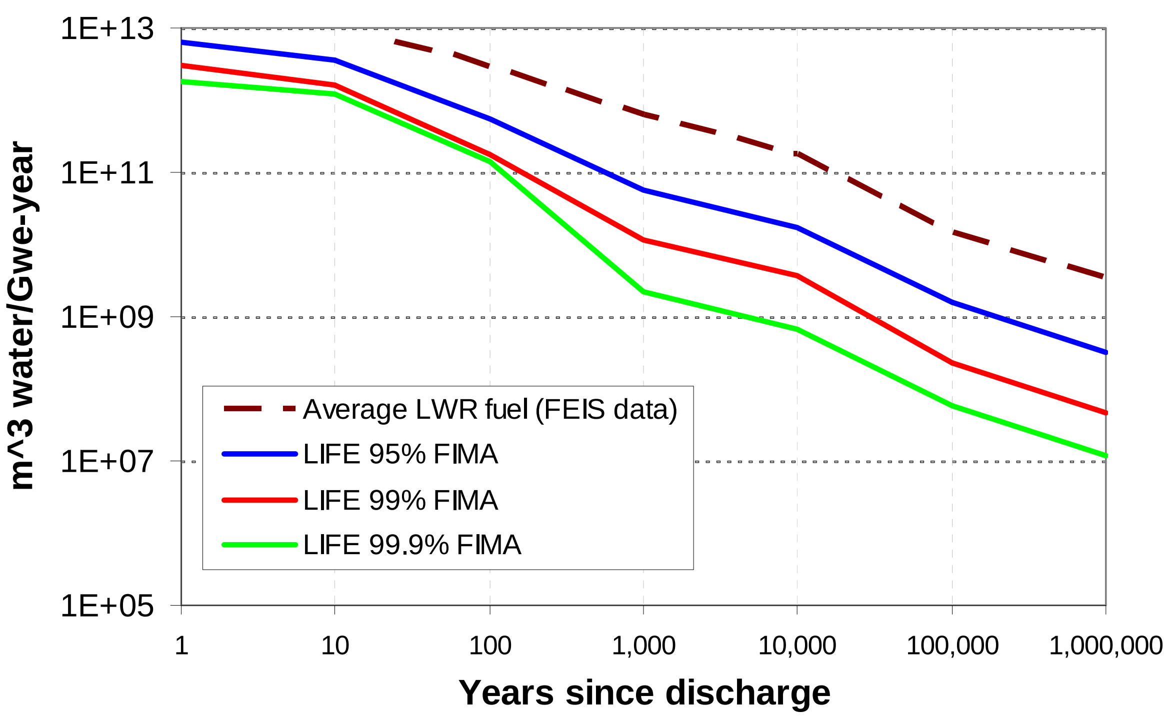


Figure 23 – Ingestion radiotoxicity (a) per metric ton of initial heavy metal; and (b) per GWe-year of generated electricity.

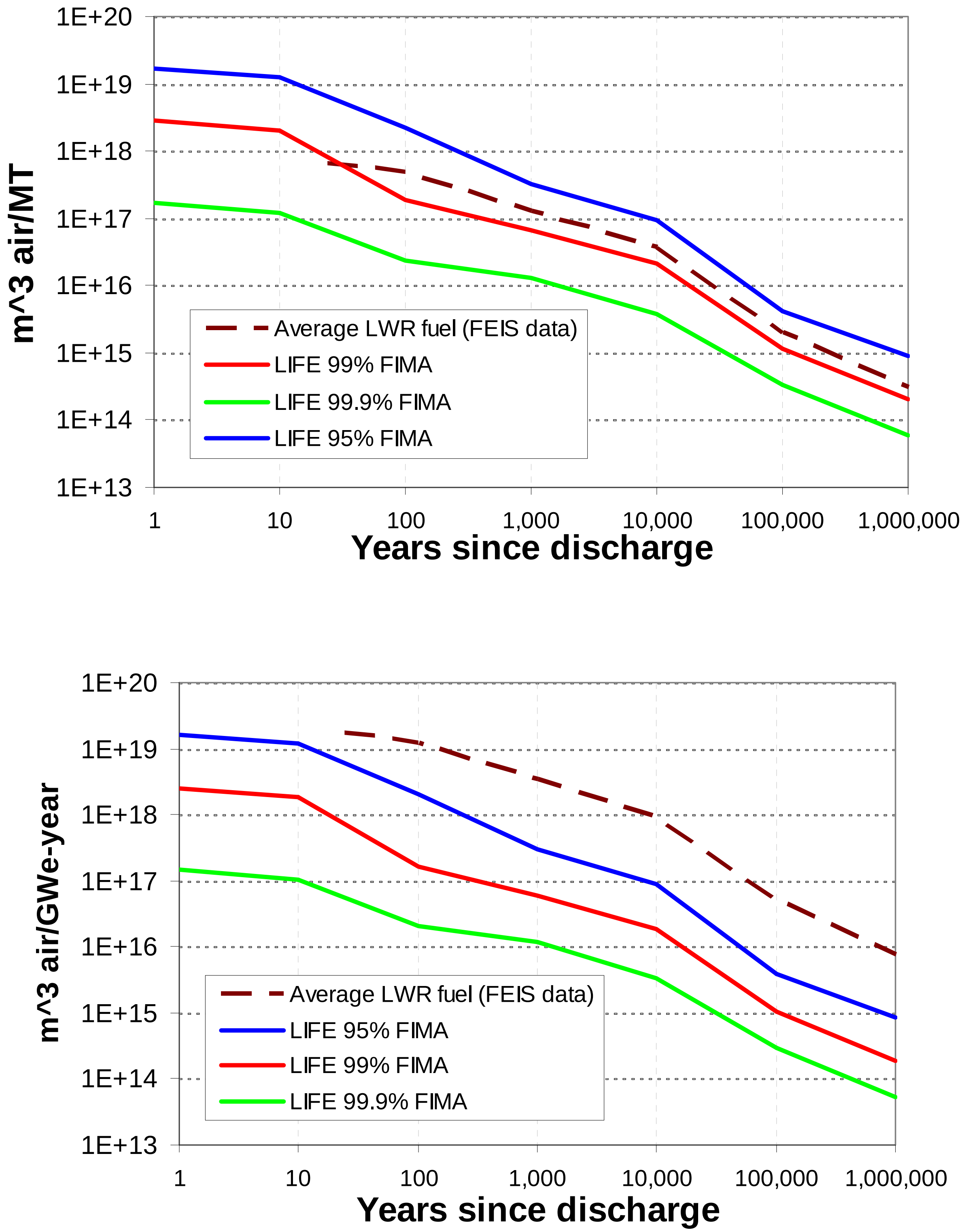


Figure 24 – Inhalation radiotoxicity, (a) per metric ton of initial heavy metal; and (b) per GWe-year of generated electricity

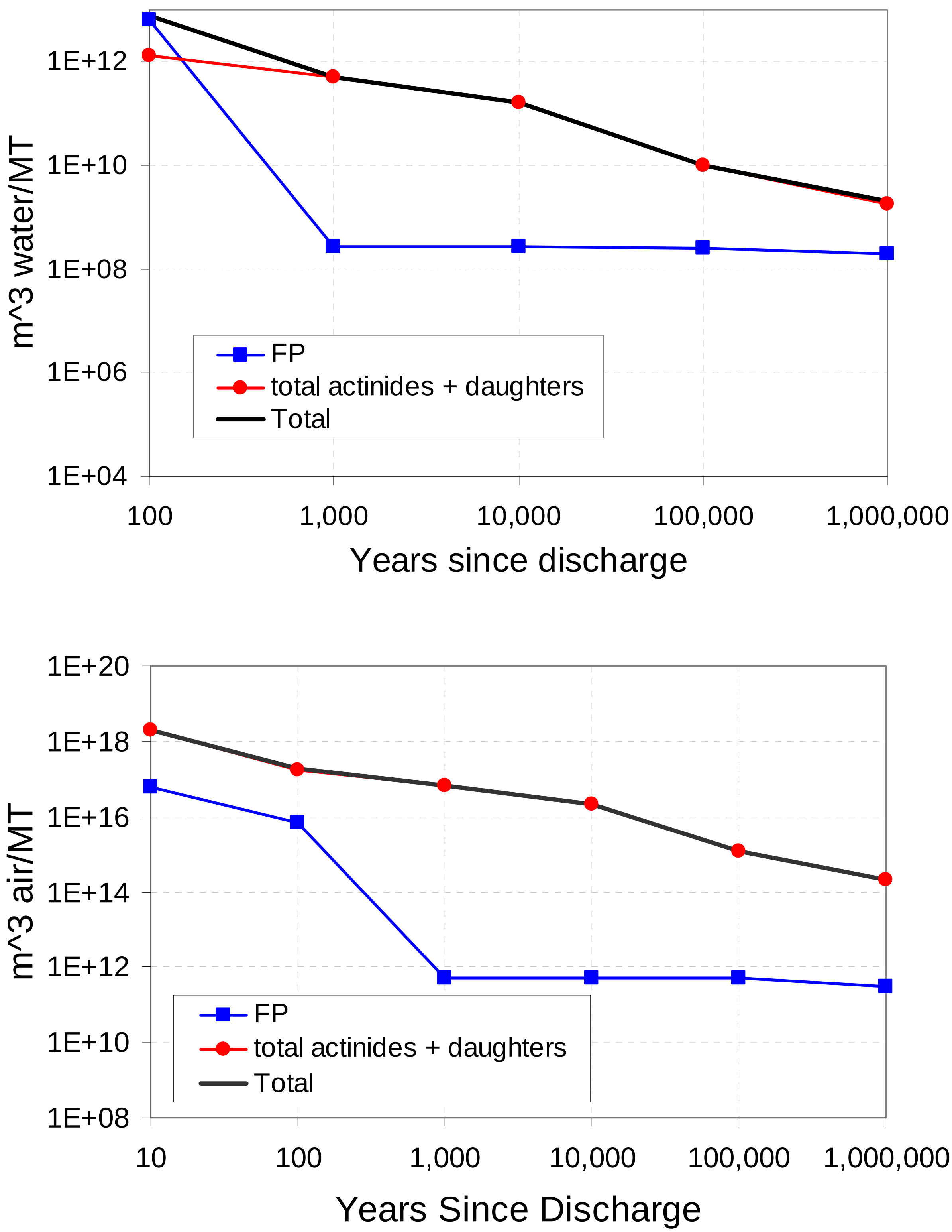


Figure 25 – The (a) ingestion and (b) inhalation radiotoxicity of spent LIFE fuel, like LWR fuel, is dominated by decay the actinides.

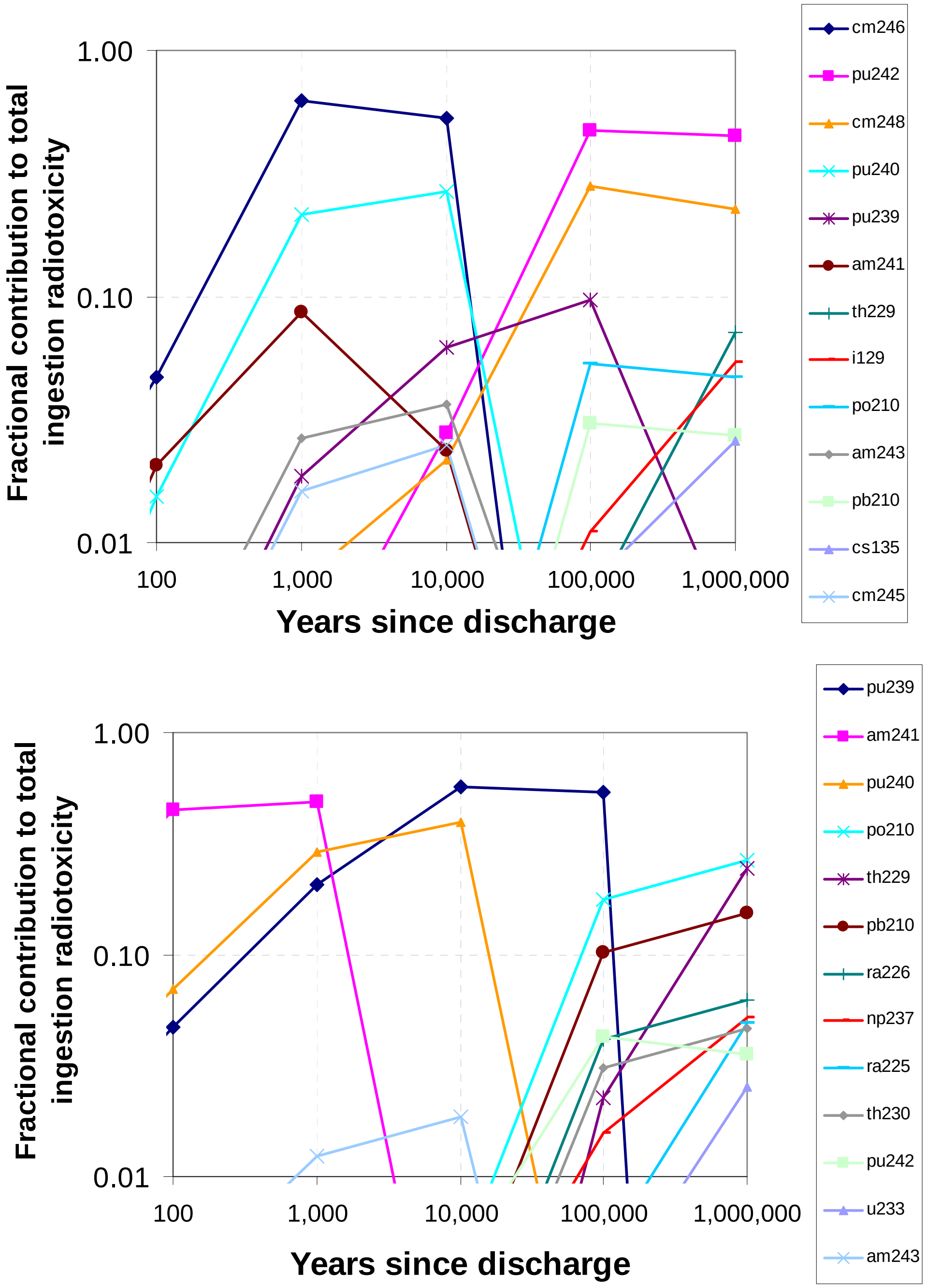


Figure 26 – Primary nuclides responsible for the intrinsic long-term ingestion radiotoxicity hazard in (a) spent LIFE fuel with 99% FIMA burnup, and (b) average spent LWR fuel. Plotted are all radionuclides that contribute more than 2% of the total ingestion radiotoxicity at any time between 10^3 and 10^6 years after discharge.

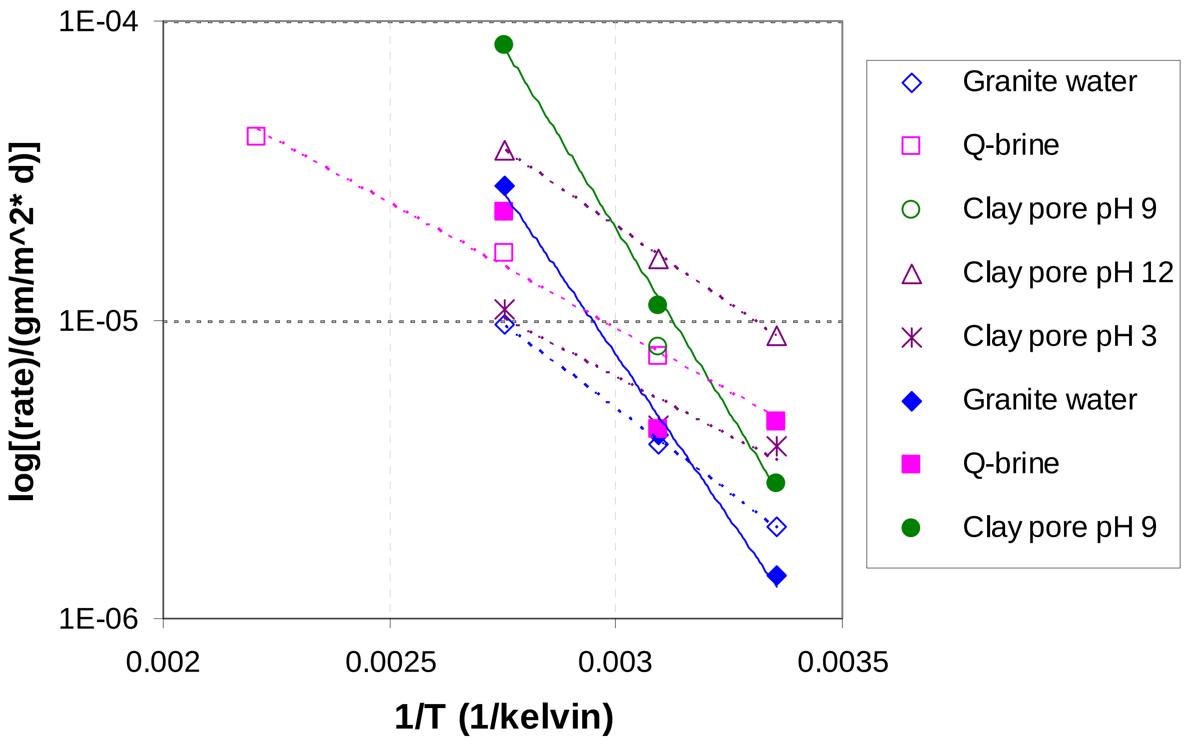


Figure 27 – Dissolution rates (gm/m^2/day) of unirradiated (open symbols) and irradiated (closed symbols) SiC. Data from Fachinger *et al*., [2006]. Legend refers to the different composition solutions used in the experiments.

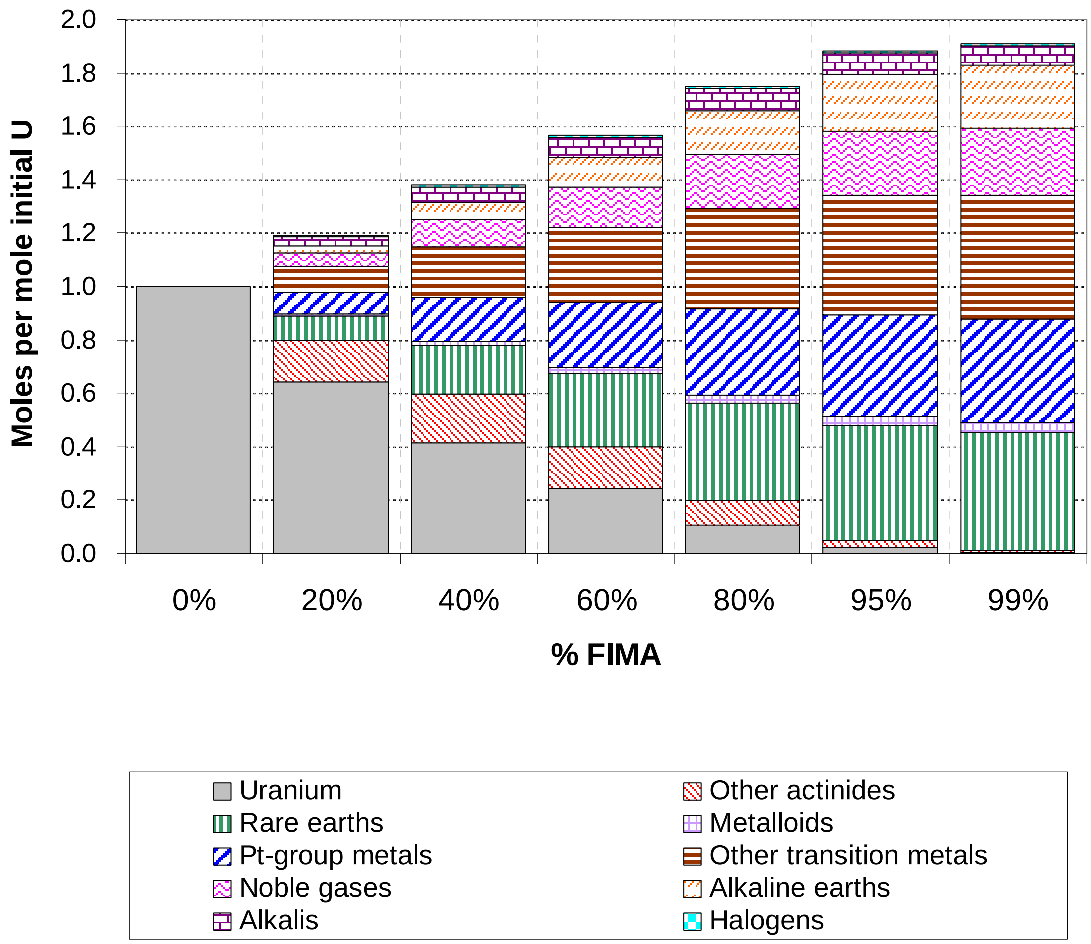
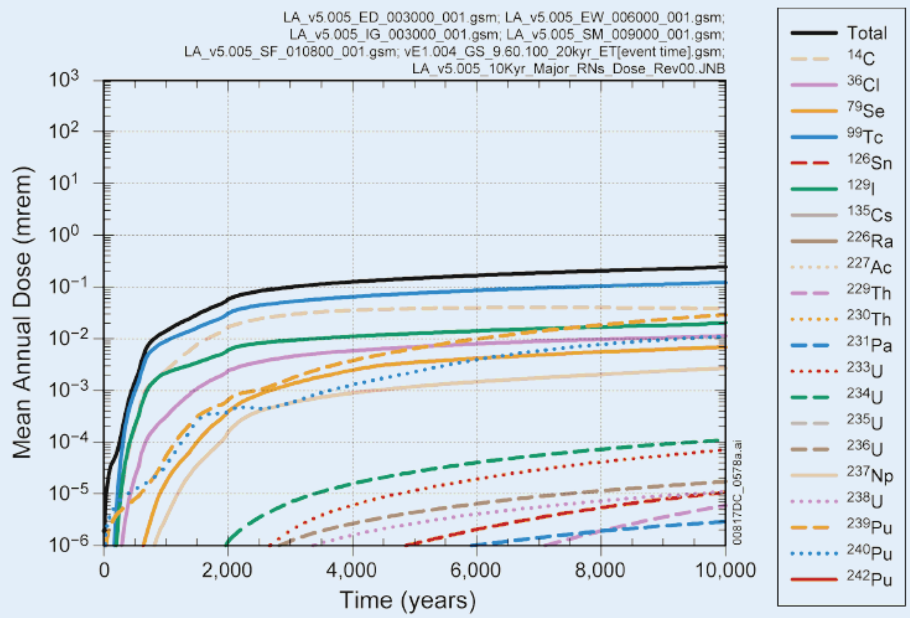
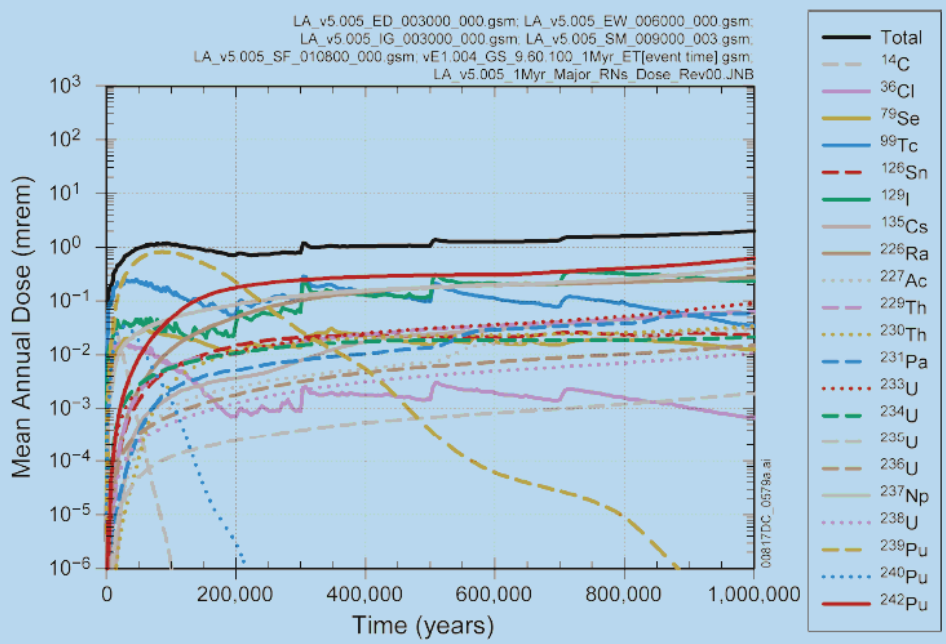


Figure 28 – Evolution of the chemical composition of a depleted uranium fuel as a function of burnup, showing the drastic changes in composition that result from the complete fission of the initial uranium.



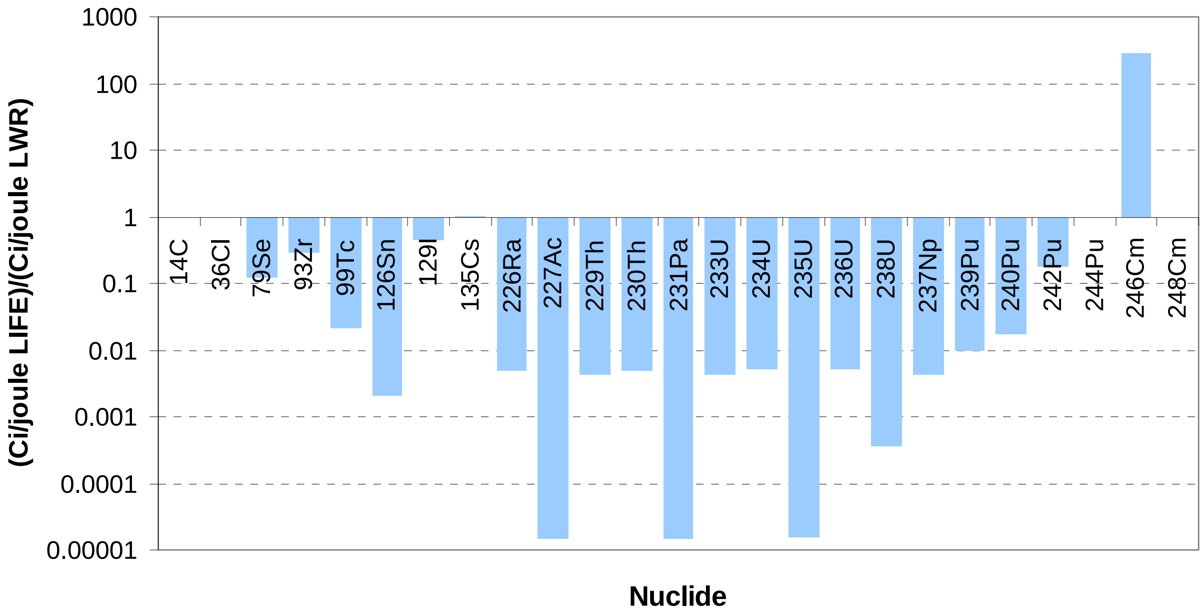
Source: Output DTNs: MO0710ADTSPAWO.000 [DIRS 183752]; MO0710PLOTSFIG.000 [DIRS 185207]; and MO0709TSPAREGS.000 [DIRS 182976].



Source: Output DTNs: MO0710ADTSPAWO.000 [DIRS 183752]; MO0710PLOTSFIG.000 [DIRS 185207]; and MO0709TSPAREGS.000 [DIRS 182976].

Figure ES-43[a]. Contribution of Individual Radionuclides to Total Mean Annual Dose for 1,000,000 Years after Repository Closure

Figure 29 – Contributions of individual radionuclides to the total mean annual dose, as calculated by the TSPA for the Yucca Mountain Repository License Application [Sandia, 2008]: (a) 0 to 10,000 years after repository closure; (b) up to 1,000,000 years after repository closure.



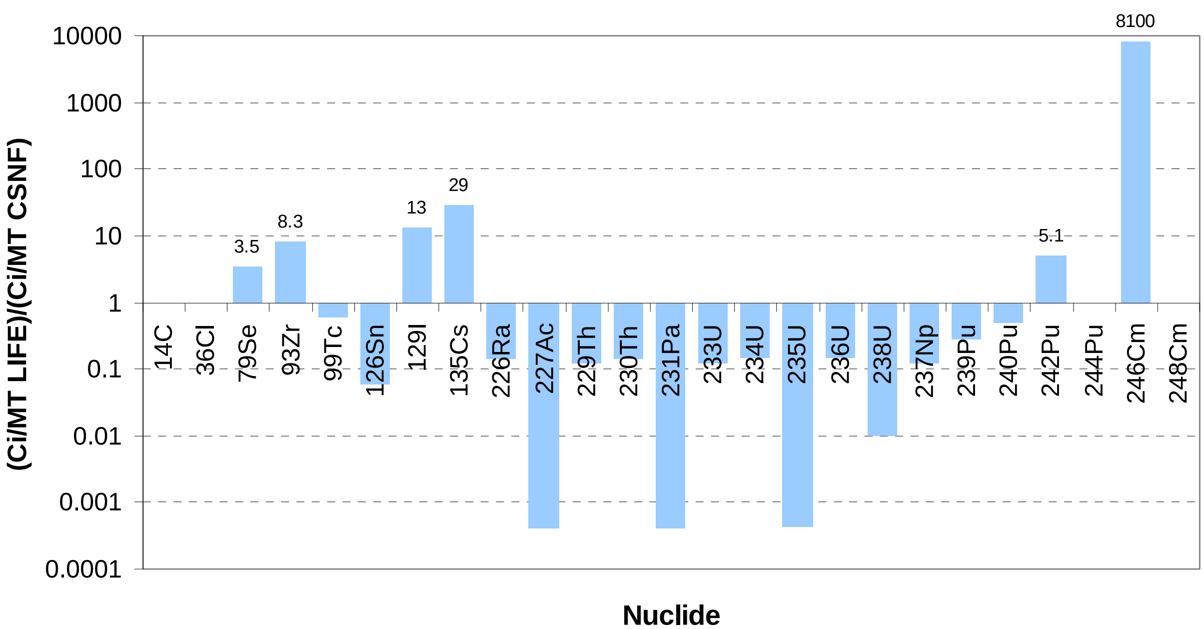


Figure 30 – Ratios of the activities of long-lived nuclides important to performance in a Yucca Mountain repository. (a) Activity ratios normalized to the energy generated; (b) Activity ratios normalized to the mass of initial heavy metal.

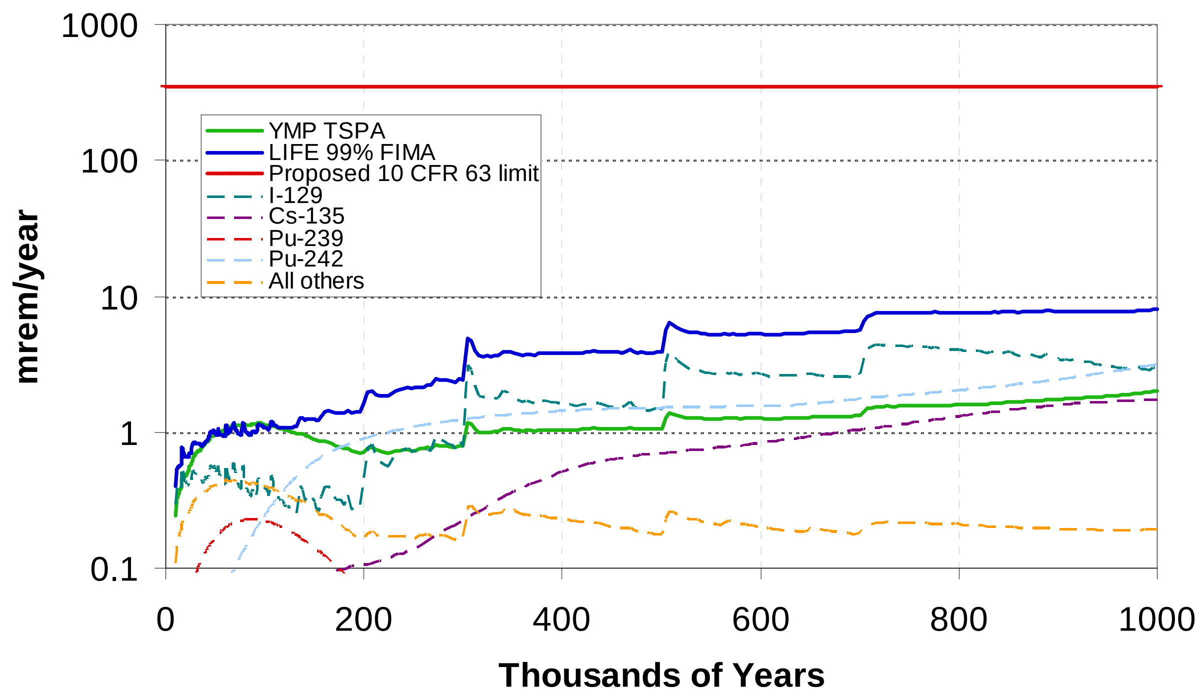


Figure 31 – Estimate of the mean annual dose for a LIFE-waste loaded Yucca Mountain repository, showing the major radionuclides contributing to dose for the LIFE case. Also shown is the corresponding curve for the YMP TSPA-LA [Sandia, 2008], and the proposed NRC limit on doses [USNRC, 2007b.

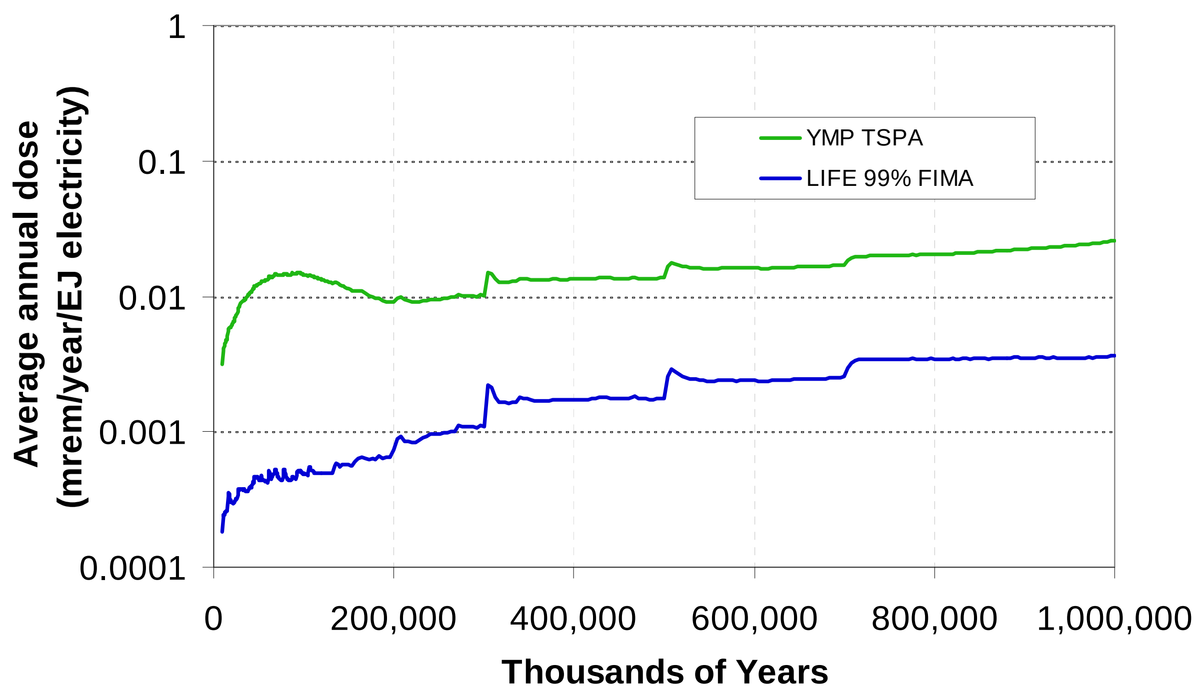


Figure 32 – Estimate of the mean annual dose for a Yucca Mountain repository loaded with either CSNF or LIFE waste, normalized to the net energy generated by those wastes. A repository containing LIFE waste would have a much lower risk/benefit ratio than a repository containing CSNF.

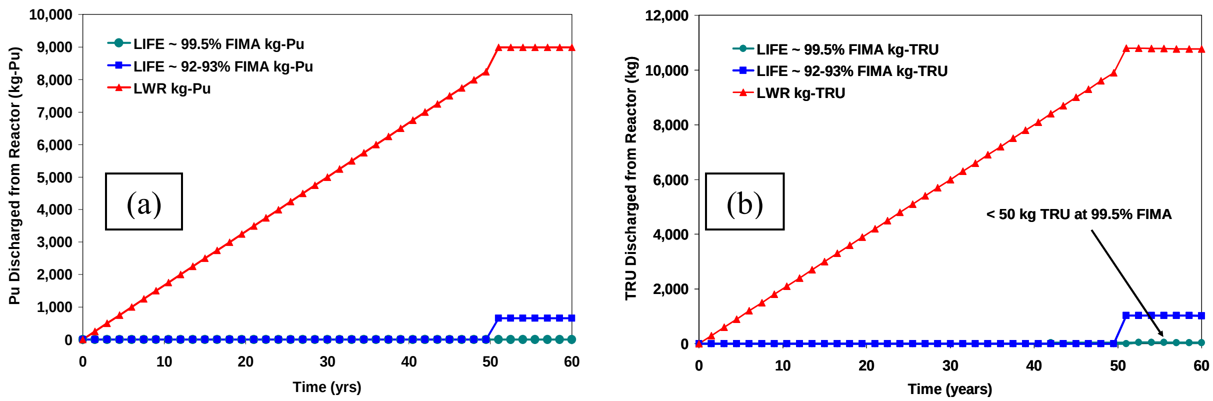


Figure 33 – (a) Plutonium leaving each power plant as a function of time: (b) TRU (including Pu) leaving each power plant vs. **time. The LIFE fuel cycle will generate less Pu and TRU per power plant than a typical LWR fuel cycle.**

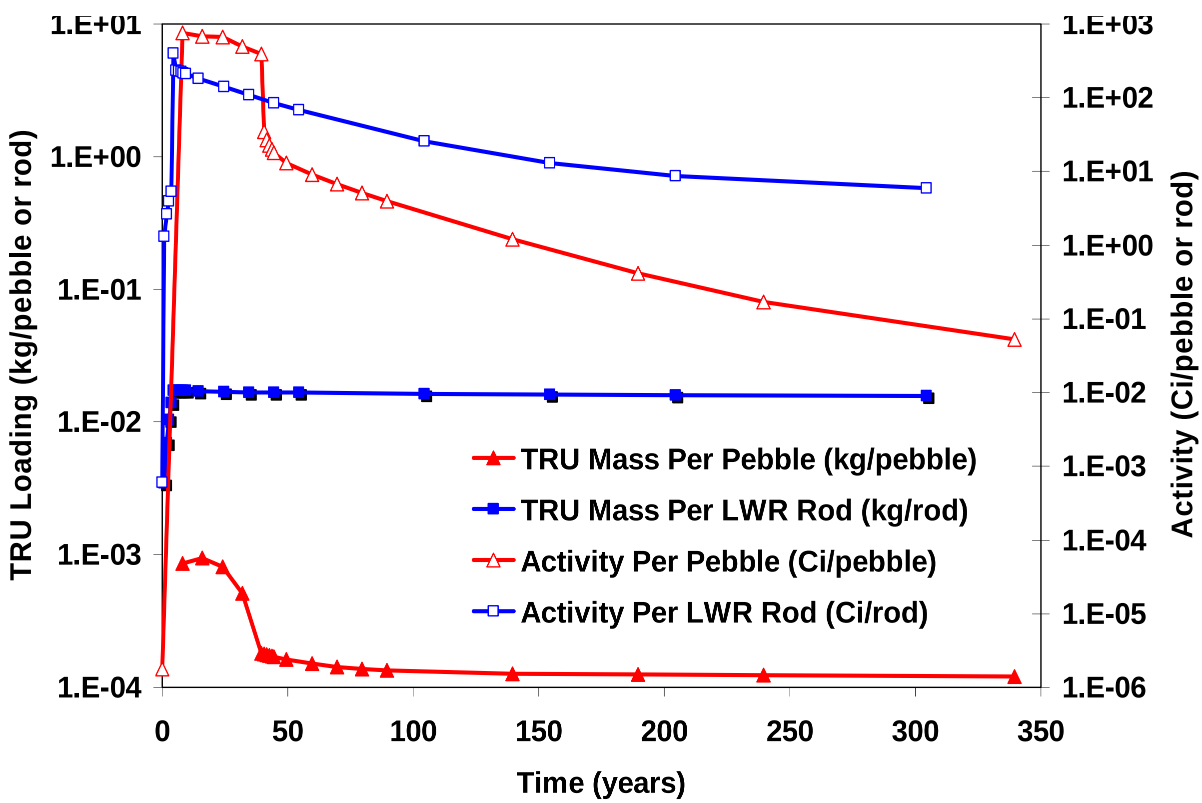


Figure 34 – Comparison of TRU mass and total activity for a single LIFE pebble and a single fuel rod.

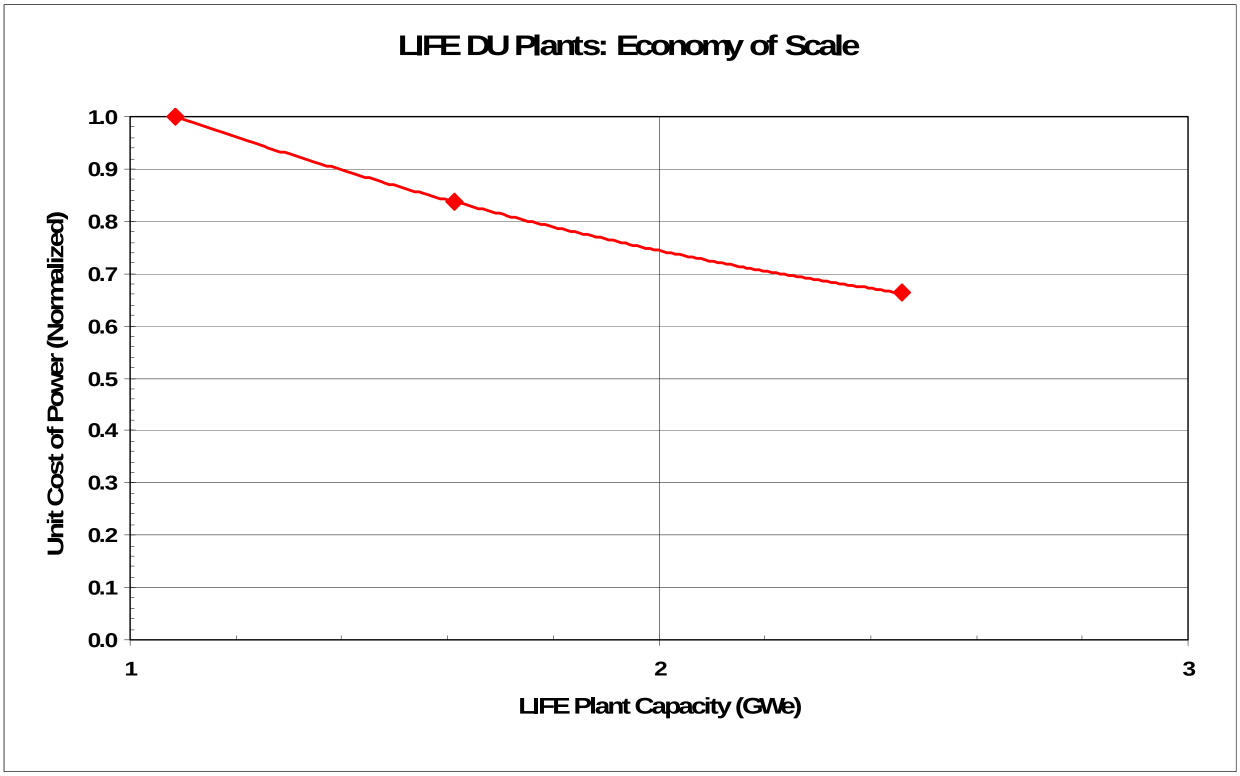


Figure 35 – Economy of scale for LIFE plants assuming Low-Incidence-Angle Fast Ignition (LIA-FI) targets, and the burning of TRISO fuel with natural or depleted uranium kernels.

Appendix A

Radionuclide Inventory as a Function of Time for 95% FIMA LIFE Fuel

Base Case 40MT Life Engine DU Fuel 95% FIMA
Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1E+00	3E+00	1E+01	3E+01	1E+02	3E+02	1E+03	3E+03	1E+04	3E+04	1E+05	3E+05	1E+06
SE 79	3.14E+00	3.14E+00	3.14E+00	3.14E+00	3.13E+00	3.13E+00	3.10E+00	3.04E+00	2.82E+00	2.28E+00	1.08E+00	1.28E-01	7.32E-05
KR 85	5.23E+04	4.59E+04	2.92E+04	8.01E+03	8.68E+01	2.10E-04	4.63E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RB 86	9.86E-02	1.61E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RB 87	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04
SR 89	2.07E+03	9.18E-02	5.35E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SR 90	4.68E+05	4.45E+05	3.76E+05	2.32E+05	4.26E+04	3.36E+02	1.47E-05	1.39E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 89M	1.99E-01	8.84E-06	5.15E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 90	4.68E+05	4.46E+05	3.76E+05	2.32E+05	4.26E+04	3.36E+02	1.47E-05	1.39E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 91	5.49E+03	9.57E-01	6.70E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ZR 93	2.24E+01	2.24E+01	2.24E+01	2.24E+01	2.24E+01	2.24E+01	2.24E+01	2.24E+01	2.23E+01	2.21E+01	2.14E+01	1.96E+01	1.43E+01
ZR 95	1.70E+04	6.24E+00	5.95E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NB 93M	9.20E-01	2.65E+00	7.64E+00	1.59E+01	2.16E+01	2.19E+01	2.19E+01	2.18E+01	2.18E+01	2.16E+01	2.09E+01	1.91E+01	1.39E+01
NB 95	3.78E+04	1.42E+01	1.31E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NB 95M	1.98E+02	7.27E-02	6.93E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TC 99	3.09E+01	3.09E+01	3.09E+01	3.09E+01	3.09E+01	3.09E+01	3.08E+01	3.06E+01	2.99E+01	2.80E+01	2.23E+01	1.16E+01	1.16E+00
RU103	3.71E+03	9.30E-03	2.31E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RU106	4.63E+05	1.17E+05	9.51E+02	1.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RH103M	3.67E+03	9.20E-03	2.29E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RH106	4.63E+05	1.17E+05	9.51E+02	1.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PD107	2.49E+00	2.49E+00	2.49E+00	2.49E+00	2.49E+00	2.49E+00	2.49E+00	2.49E+00	2.49E+00	2.48E+00	2.46E+00	2.41E+00	2.24E+00
IN115	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11	2.56E-11
SN126	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.03E-01	1.02E-01	9.70E-02	8.45E-02	5.20E-02	1.30E-02	1.02E-04
SB124	4.36E+02	9.76E-02	1.63E-14	0.00E+00	5.05E-07	7.62E-29	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SB125	3.19E+04	1.93E+04	3.33E+03	2.19E+01	1.45E-02	1.45E-02	1.45E-02	1.43E-02	1.36E-02	1.18E-02	7.28E-03	1.82E-03	1.42E-05
SB126	1.46E-02	1.46E-02	1.46E-02	1.46E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SB126M	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.03E-01	1.02E-01	9.70E-02	8.45E-02	5.20E-02	1.30E-02	1.02E-04
TE123	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10	8.61E-10
TE125M	7.86E+03	4.84E+03	8.34E+02	5.48E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I129	6.67E-01	6.67E-01	6.67E-01	6.67E-01	6.67E-01	6.67E-01	6.67E-01	6.67E-01	6.66E-01	6.66E-01	6.64E-01	6.58E-01	6.38E-01
CS134	1.58E+06	8.05E+05	7.69E+04	9.34E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CS135	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.86E+01	1.83E+01	1.72E+01	1.41E+01
CS136	1.00E-02	1.34E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CS137	1.44E+06	1.38E+06	1.17E+06	7.41E+05	1.48E+05	1.50E+03	1.55E-04	1.72E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Base Case 40MT Life Engine DU Fuel 95% FIMA (cont.)
Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1E+00	3E+00	1E+01	3E+01	1E+02	3E+02	1E+03	3E+03	1E+04	3E+04	1E+05	3E+05	1E+06
BA137M	1.36E+06	1.30E+06	1.11E+06	7.01E+05	1.40E+05	1.42E+03	1.47E-04	1.63E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BA140	2.26E-03	1.25E-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LA138	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06	1.38E-06
LA140	2.60E-03	1.44E-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CE141	4.40E+02	7.54E-05	1.57E-28	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CE142	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09	1.32E-09
CE144	2.84E+05	4.80E+04	9.55E+01	1.83E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR143	7.68E-03	4.87E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR144	2.84E+05	4.80E+04	9.55E+01	1.83E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR144M	4.25E+03	7.20E+02	1.43E+00	2.75E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ND144	4.71E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08	4.72E-08
PM147	1.06E+05	6.23E+04	9.80E+03	4.96E+01	4.60E-07	5.14E-30	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SM147	2.74E-06	3.82E-06	5.12E-06	5.36E-06	5.36E-06	5.36E-06	5.36E-06	5.36E-06	5.36E-06	5.36E-06	5.36E-06	5.36E-06	5.36E-06
SM148	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09	2.07E-09
SM149	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11	1.79E-11
SM151	3.49E+03	3.43E+03	3.25E+03	2.79E+03	1.63E+03	3.49E+02	1.59E+00	3.24E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU152	5.87E+01	5.30E+01	3.70E+01	1.33E+01	3.67E-01	1.29E-05	3.37E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU154	1.08E+05	9.18E+04	5.22E+04	1.04E+04	3.67E+01	3.62E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU155	4.15E+04	3.12E+04	1.14E+04	6.55E+02	2.93E-02	1.10E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU156	1.49E-01	4.91E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GD152	1.87E-11	1.89E-11	1.94E-11	2.03E-11	2.07E-11	2.07E-11	2.07E-11	2.07E-11	2.07E-11	2.07E-11	2.07E-11	2.07E-11	2.07E-11
TB160	3.69E+04	3.36E+01	7.61E-10	3.16E-40	6.97E-13	1.92E-11	3.96E-10	3.22E-09	1.91E-08	6.65E-08	1.48E-07	1.52E-07	2.48E-08
TL206	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.92E-11	1.35E-09	2.79E-08	2.27E-07	1.35E-06	4.69E-06	1.04E-05	1.07E-05	1.75E-06
TL207	8.90E-11	7.87E-10	8.14E-09	6.05E-08	3.95E-07	1.51E-06	5.59E-06	1.64E-05	5.10E-05	1.26E-04	2.36E-04	2.68E-04	2.68E-04
TL208	4.57E-01	1.19E+00	2.30E+00	2.18E+00	1.09E+00	1.50E-01	1.43E-04	3.24E-09	2.60E-08	1.38E-07	5.92E-07	1.89E-06	6.35E-06
TL209	4.59E-13	3.95E-12	4.23E-11	3.92E-10	6.41E-09	1.22E-07	3.27E-06	5.06E-05	6.73E-04	4.76E-03	2.19E-02	5.02E-02	5.64E-02
TL210	2.83E-13	2.83E-12	4.22E-11	6.44E-10	1.57E-08	2.75E-07	4.38E-06	3.56E-05	2.11E-04	7.36E-04	1.64E-03	1.68E-03	2.75E-04
PB209	2.13E-11	1.83E-10	1.96E-09	1.82E-08	2.97E-07	5.66E-06	1.51E-04	2.34E-03	3.12E-02	2.21E-01	1.01E+00	2.33E+00	2.61E+00
PB210	1.35E-11	3.91E-10	1.76E-08	6.65E-07	3.67E-05	1.01E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.80E+00	8.01E+00	1.31E+00
PB211	8.93E-11	7.90E-10	8.16E-09	6.06E-08	3.96E-07	1.52E-06	5.61E-06	1.65E-05	5.11E-05	1.26E-04	2.37E-04	2.69E-04	2.69E-04
PB212	1.27E+00	3.32E+00	6.39E+00	6.07E+00	3.03E+00	4.16E-01	3.99E-04	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
PB214	1.35E-09	1.35E-08	2.01E-07	3.07E-06	7.49E-05	1.31E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.79E+00	8.01E+00	1.31E+00
BI210	1.35E-11	3.91E-10	1.76E-08	6.66E-07	3.67E-05	1.01E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.80E+00	8.01E+00	1.31E+00

Base Case 40MT Life Engine DU Fuel 95% FIMA (cont.)
Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1E+00	3E+00	1E+01	3E+01	1E+02	3E+02	1E+03	3E+03	1E+04	3E+04	1E+05	3E+05	1E+06
BI211	8.93E-11	7.90E-10	8.16E-09	6.06E-08	3.96E-07	1.52E-06	5.61E-06	1.65E-05	5.11E-05	1.26E-04	2.37E-04	2.69E-04	2.69E-04
BI212	1.27E+00	3.32E+00	6.39E+00	6.07E+00	3.03E+00	4.16E-01	3.99E-04	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
BI213	2.13E-11	1.83E-10	1.96E-09	1.82E-08	2.97E-07	5.66E-06	1.51E-04	2.34E-03	3.11E-02	2.21E-01	1.01E+00	2.33E+00	2.61E+00
BI214	1.35E-09	1.35E-08	2.01E-07	3.07E-06	7.49E-05	1.31E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.80E+00	8.01E+00	1.31E+00
BI215	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.16E-10
PO210	4.33E-12	2.35E-10	1.76E-08	6.66E-07	3.67E-05	1.01E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.80E+00	8.01E+00	1.31E+00
PO211	2.44E-13	2.16E-12	2.23E-11	1.65E-10	1.08E-09	4.14E-09	1.53E-08	4.50E-08	1.40E-07	3.44E-07	6.46E-07	7.34E-07	7.34E-07
PO212	8.14E-01	2.12E+00	4.09E+00	3.89E+00	1.94E+00	2.67E-01	2.56E-04	5.78E-09	4.63E-08	2.45E-07	1.06E-06	3.36E-06	1.13E-05
PO213	2.08E-11	1.79E-10	1.92E-09	1.78E-08	2.90E-07	5.54E-06	1.48E-04	2.29E-03	3.05E-02	2.16E-01	9.90E-01	2.28E+00	2.55E+00
PO214	1.35E-09	1.35E-08	2.01E-07	3.07E-06	7.49E-05	1.31E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.79E+00	8.01E+00	1.31E+00
PO215	8.93E-11	7.90E-10	8.16E-09	6.06E-08	3.96E-07	1.52E-06	5.61E-06	1.65E-05	5.11E-05	1.26E-04	2.37E-04	2.69E-04	2.69E-04
PO216	1.27E+00	3.32E+00	6.39E+00	6.07E+00	3.03E+00	4.16E-01	3.99E-04	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
PO218	1.35E-09	1.35E-08	2.01E-07	3.07E-06	7.49E-05	1.31E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.80E+00	8.01E+00	1.31E+00
AT215	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.58E-12	6.07E-12	2.24E-11	6.59E-11	2.04E-10	5.04E-10	9.46E-10	1.08E-09	1.08E-09
AT217	2.13E-11	1.83E-10	1.96E-09	1.82E-08	2.97E-07	5.66E-06	1.51E-04	2.34E-03	3.12E-02	2.21E-01	1.01E+00	2.33E+00	2.61E+00
AT218	2.69E-13	2.69E-12	4.02E-11	6.13E-10	1.50E-08	2.62E-07	4.17E-06	3.39E-05	2.01E-04	7.01E-04	1.56E-03	1.60E-03	2.61E-04
AT219	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.23E-10
RN217	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.56E-11	6.79E-10	1.82E-08	2.81E-07	3.74E-06	2.65E-05	1.21E-04	2.79E-04	3.13E-04
RN218	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.50E-11	2.62E-10	4.17E-09	3.39E-08	2.01E-07	7.01E-07	1.56E-06	1.60E-06	2.61E-07
RN219	8.93E-11	7.90E-10	8.16E-09	6.06E-08	3.96E-07	1.52E-06	5.61E-06	1.65E-05	5.11E-05	1.26E-04	2.37E-04	2.69E-04	2.69E-04
RN220	1.27E+00	3.32E+00	6.39E+00	6.07E+00	3.03E+00	4.16E-01	3.99E-04	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
RN222	1.35E-09	1.35E-08	2.01E-07	3.07E-06	7.49E-05	1.31E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.80E+00	8.01E+00	1.31E+00
FR221	2.13E-11	1.83E-10	1.96E-09	1.82E-08	2.97E-07	5.66E-06	1.51E-04	2.34E-03	3.12E-02	2.21E-01	1.01E+00	2.33E+00	2.61E+00
FR223	1.23E-12	1.09E-11	1.13E-10	8.36E-10	5.46E-09	2.09E-08	7.74E-08	2.27E-07	7.05E-07	1.74E-06	3.26E-06	3.71E-06	3.71E-06
RA223	8.93E-11	7.90E-10	8.16E-09	6.06E-08	3.96E-07	1.52E-06	5.61E-06	1.65E-05	5.11E-05	1.26E-04	2.37E-04	2.69E-04	2.69E-04
RA224	1.27E+00	3.32E+00	6.39E+00	6.07E+00	3.03E+00	4.16E-01	3.99E-04	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
RA225	2.13E-11	1.83E-10	1.96E-09	1.82E-08	2.97E-07	5.66E-06	1.51E-04	2.34E-03	3.12E-02	2.21E-01	1.01E+00	2.33E+00	2.61E+00
RA226	1.35E-09	1.35E-08	2.01E-07	3.07E-06	7.49E-05	1.31E-03	2.08E-02	1.70E-01	1.01E+00	3.50E+00	7.80E+00	8.01E+00	1.31E+00
RA228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-11	2.30E-10	1.39E-09	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
AC225	2.13E-11	1.83E-10	1.96E-09	1.82E-08	2.97E-07	5.66E-06	1.51E-04	2.34E-03	3.12E-02	2.21E-01	1.01E+00	2.33E+00	2.61E+00
AC227	8.93E-11	7.89E-10	8.16E-09	6.06E-08	3.96E-07	1.52E-06	5.61E-06	1.65E-05	5.11E-05	1.26E-04	2.37E-04	2.69E-04	2.69E-04
AC228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-11	2.30E-10	1.39E-09	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
TH227	8.80E-11	7.78E-10	8.05E-09	5.98E-08	3.91E-07	1.50E-06	5.53E-06	1.63E-05	5.04E-05	1.24E-04	2.33E-04	2.65E-04	2.65E-04

Base Case 40MT Life Engine DU Fuel 95% FIMA (cont.)

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1E+00	3E+00	1E+01	3E+01	1E+02	3E+02	1E+03	3E+03	1E+04	3E+04	1E+05	3E+05	1E+06
TH228	1.27E+00	3.31E+00	6.39E+00	6.07E+00	3.03E+00	4.16E-01	3.99E-04	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
TH229	2.13E-11	1.83E-10	1.96E-09	1.82E-08	2.97E-07	5.66E-06	1.51E-04	2.34E-03	3.12E-02	2.21E-01	1.01E+00	2.33E+00	2.61E+00
TH230	6.39E-06	2.23E-05	1.10E-04	6.14E-04	4.70E-03	2.64E-02	1.22E-01	3.94E-01	1.30E+00	3.48E+00	7.76E+00	7.99E+00	1.31E+00
TH231	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.69E-04	2.69E-04	2.69E-04	2.69E-04
TH232	5.31E-13	1.59E-12	5.33E-12	1.62E-11	5.92E-11	2.30E-10	1.39E-09	9.01E-09	7.22E-08	3.83E-07	1.65E-06	5.25E-06	1.77E-05
TH234	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.06E-03	8.07E-03	8.14E-03	8.36E-03	8.84E-03	9.63E-03
PA231	5.67E-09	1.70E-08	5.68E-08	1.70E-07	5.66E-07	1.70E-06	5.61E-06	1.65E-05	5.11E-05	1.26E-04	2.37E-04	2.69E-04	2.69E-04
PA233	8.59E-02	8.68E-02	9.31E-02	1.30E-01	3.11E-01	7.64E-01	1.61E+00	2.18E+00	2.70E+00	3.22E+00	3.28E+00	3.07E+00	2.45E+00
PA234	1.05E-05	1.05E-05	1.05E-05	1.05E-05	1.05E-05	1.05E-05	1.05E-05	1.05E-05	1.05E-05	1.06E-05	1.09E-05	1.15E-05	1.25E-05
PA234M	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.06E-03	8.07E-03	8.14E-03	8.36E-03	8.84E-03	9.63E-03
U232	4.55E+00	5.66E+00	6.82E+00	5.91E+00	2.95E+00	4.05E-01	3.88E-04	9.22E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U233	4.20E-07	1.25E-06	4.06E-06	1.36E-05	8.01E-05	5.58E-04	4.39E-03	2.15E-02	9.59E-02	3.42E-01	1.12E+00	2.30E+00	2.60E+00
U234	7.51E-01	9.76E-01	1.74E+00	3.70E+00	8.55E+00	1.38E+01	1.51E+01	1.50E+01	1.47E+01	1.39E+01	1.14E+01	6.50E+00	9.10E-01
U235	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.68E-04	2.69E-04	2.69E-04	2.69E-04	2.69E-04
U236	1.08E-02	1.08E-02	1.09E-02	1.13E-02	1.37E-02	2.10E-02	4.57E-02	1.07E-01	2.43E-01	3.51E-01	3.66E-01	3.64E-01	3.56E-01
U237	6.09E+00	5.54E+00	3.95E+00	1.52E+00	6.06E-02	8.64E-03	8.16E-03	6.93E-03	3.92E-03	7.66E-04	2.54E-06	2.09E-13	0.00E+00
U238	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.05E-03	8.06E-03	8.07E-03	8.14E-03	8.36E-03	8.84E-03	9.63E-03
U240	1.05E-04	1.05E-04	1.05E-04	1.05E-04	1.06E-04	1.09E-04	1.20E-04	1.50E-04	2.55E-04	5.48E-04	1.48E-03	3.52E-03	6.56E-03
NP237	8.59E-02	8.68E-02	9.31E-02	1.30E-01	3.11E-01	7.64E-01	1.61E+00	2.18E+00	2.70E+00	3.22E+00	3.28E+00	3.07E+00	2.45E+00
NP239	3.32E+02	3.32E+02	3.32E+02	3.31E+02	3.29E+02	3.23E+02	3.02E+02	2.51E+02	1.30E+02	1.98E+01	5.48E-02	2.74E-02	2.66E-02
NP240	1.05E-04	1.05E-04	1.05E-04	1.05E-04	1.06E-04	1.09E-04	1.20E-04	1.50E-04	2.55E-04	5.48E-04	1.48E-03	3.52E-03	6.56E-03
PU236	7.69E+01	4.77E+01	8.95E+00	7.51E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU237	5.40E+00	7.55E-05	7.72E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU238	3.99E+04	3.96E+04	3.75E+04	3.20E+04	1.84E+04	3.79E+03	1.50E+01	2.05E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU239	2.56E+02	2.56E+02	2.56E+02	2.56E+02	2.56E+02	2.57E+02	2.58E+02	2.59E+02	2.45E+02	1.61E+02	2.27E+01	9.83E-02	2.66E-02
PU240	2.07E+02	2.85E+02	5.17E+02	9.18E+02	1.24E+03	1.23E+03	1.15E+03	9.28E+02	4.43E+02	5.36E+01	3.44E-02	3.52E-03	6.56E-03
PU241	2.48E+05	2.26E+05	1.61E+05	6.18E+04	2.47E+03	3.53E+02	3.33E+02	2.83E+02	1.60E+02	3.13E+01	1.04E-01	8.55E-09	0.00E+00
PU242	8.55E+00	8.55E+00	8.57E+00	8.61E+00	8.75E+00	9.14E+00	1.04E+01	1.34E+01	1.89E+01	2.11E+01	1.87E+01	1.29E+01	3.52E+00
PU243	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.77E-02	2.77E-02	2.74E-02	2.66E-02
PU244	1.05E-04	1.05E-04	1.05E-04	1.05E-04	1.06E-04	1.10E-04	1.20E-04	1.51E-04	2.56E-04	5.48E-04	1.48E-03	3.52E-03	6.57E-03
AM241	9.36E+02	1.69E+03	3.81E+03	6.95E+03	8.06E+03	6.00E+03	2.18E+03	3.70E+02	1.60E+02	3.13E+01	1.04E-01	9.01E-09	0.00E+00
AM243	3.32E+02	3.32E+02	3.32E+02	3.31E+02	3.29E+02	3.23E+02	3.02E+02	2.51E+02	1.30E+02	1.98E+01	5.48E-02	2.74E-02	2.66E-02
CM242	7.48E+04	3.34E+03	6.33E-02	2.03E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Base Case 40MT Life Engine DU Fuel 95% FIMA (cont.)
Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1E+00	3E+00	1E+01	3E+01	1E+02	3E+02	1E+03	3E+03	1E+04	3E+04	1E+05	3E+05	1E+06
CM243	4.04E+02	3.86E+02	3.29E+02	2.07E+02	4.11E+01	4.04E-01	3.82E-08	3.26E-28	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CM244	3.86E+05	3.57E+05	2.73E+05	1.27E+05	8.70E+03	4.11E+00	9.36E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CM245	3.61E+02	3.61E+02	3.60E+02	3.60E+02	3.58E+02	3.52E+02	3.32E+02	2.82E+02	1.60E+02	3.12E+01	1.04E-01	8.53E-09	0.00E+00
CM246	1.09E+03	1.09E+03	1.09E+03	1.09E+03	1.07E+03	1.04E+03	9.41E+02	7.02E+02	2.52E+02	1.34E+01	4.73E-04	8.89E-17	0.00E+00
CM247	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.78E-02	2.77E-02	2.77E-02	2.74E-02	2.66E-02
CM248	1.92E+00	1.92E+00	1.92E+00	1.92E+00	1.92E+00	1.92E+00	1.91E+00	1.91E+00	1.88E+00	1.80E+00	1.56E+00	1.04E+00	2.50E-01
Fission Products	7.27E+06	4.97E+06	3.22E+06	1.93E+06	3.76E+05	4.04E+03	1.02E+02	1.00E+02	9.90E+01	9.60E+01	8.72E+01	7.07E+01	4.63E+01
Actinides & Daughters	7.53E+05	6.31E+05	4.79E+05	2.31E+05	4.13E+04	1.37E+04	5.85E+03	3.36E+03	1.73E+03	4.42E+02	1.49E+02	1.28E+02	4.67E+01
Total	8.03E+06	5.60E+06	3.70E+06	2.16E+06	4.17E+05	1.78E+04	5.95E+03	3.46E+03	1.83E+03	5.38E+02	2.36E+02	1.99E+02	9.30E+01

Appendix B

Radionuclide Inventory as a Function of Time for 99% FIMA LIFE Fuel **Base Case 40MT Life Engine DU Fuel 99% FIMA**

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
SE 79	1.66E+00	1.66E+00	1.66E+00	1.66E+00	1.66E+00	1.66E+00	1.64E+00	1.61E+00	1.49E+00	1.21E+00	5.72E-01	6.77E-02	3.88E-05
KR 85	5.54E+04	4.87E+04	3.10E+04	8.50E+03	9.20E+01	2.23E-04	4.91E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RB 86	2.40E-01	3.93E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RB 87	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04	2.93E-04
SR 89	1.31E+03	5.80E-02	3.38E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SR 90	4.36E+05	4.15E+05	3.50E+05	2.16E+05	3.97E+04	3.13E+02	1.37E-05	1.30E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 89M	1.26E-01	5.59E-06	3.26E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 90	4.36E+05	4.15E+05	3.51E+05	2.16E+05	3.97E+04	3.14E+02	1.37E-05	1.30E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 91	3.13E+03	5.46E-01	3.82E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ZR 93	2.12E+01	2.12E+01	2.12E+01	2.12E+01	2.12E+01	2.12E+01	2.12E+01	2.12E+01	2.11E+01	2.09E+01	2.02E+01	1.85E+01	1.35E+01
ZR 95	1.27E+04	4.67E+00	4.45E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NB 93M	8.69E-01	2.50E+00	7.22E+00	1.50E+01	2.04E+01	2.07E+01	2.06E+01	2.06E+01	2.06E+01	2.04E+01	1.97E+01	1.80E+01	1.31E+01
NB 95	2.83E+04	1.06E+01	9.82E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NB 95M	1.48E+02	5.44E-02	5.19E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TC 99	9.07E+00	9.07E+00	9.07E+00	9.07E+00	9.07E+00	9.06E+00	9.04E+00	8.98E+00	8.78E+00	8.22E+00	6.53E+00	3.39E+00	3.41E-01
RU103	7.20E+03	1.80E-02	4.49E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RU106	2.69E+05	6.80E+04	5.52E+02	5.88E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RH103M	7.13E+03	1.79E-02	4.44E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RH106	2.69E+05	6.80E+04	5.52E+02	5.88E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PD107	2.09E+00	2.09E+00	2.09E+00	2.09E+00	2.09E+00	2.09E+00	2.09E+00	2.09E+00	2.09E+00	2.09E+00	2.07E+00	2.03E+00	1.88E+00
IN115	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12	3.71E-12
SN126	5.97E-02	5.97E-02	5.97E-02	5.97E-02	5.96E-02	5.96E-02	5.93E-02	5.85E-02	5.57E-02	4.85E-02	2.98E-02	7.46E-03	5.83E-05
SB124	6.16E+02	1.38E-01	2.31E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SB125	2.62E+04	1.59E+04	2.73E+03	1.80E+01	4.14E-07	6.25E-29	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SB126	8.36E-03	8.36E-03	8.36E-03	8.35E-03	8.35E-03	8.34E-03	8.30E-03	8.18E-03	7.80E-03	6.78E-03	4.18E-03	1.04E-03	8.16E-06
SB126M	5.97E-02	5.97E-02	5.97E-02	5.97E-02	5.96E-02	5.96E-02	5.93E-02	5.85E-02	5.57E-02	4.85E-02	2.98E-02	7.46E-03	5.83E-05
TE123	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10	4.87E-10
TE125M	6.46E+03	3.97E+03	6.84E+02	4.50E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I129	4.80E-01	4.80E-01	4.80E-01	4.80E-01	4.80E-01	4.80E-01	4.80E-01	4.80E-01	4.80E-01	4.80E-01	4.78E-01	4.74E-01	4.60E-01
CS134	1.03E+06	5.25E+05	5.01E+04	6.09E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

CS135	1.64E+01	1.64E+01	1.64E+01	1.64E+01	1.64E+01	1.64E+01	1.64E+01	1.64E+01	1.63E+01	1.62E+01	1.59E+01	1.50E+01	1.23E+01
CS136	2.64E-02	3.53E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Base Case 40MT Life Engine DU Fuel 99% FIMA (cont.)

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
CS137	1.35E+06	1.29E+06	1.10E+06	6.95E+05	1.39E+05	1.40E+03	1.46E-04	1.61E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BA137M	1.28E+06	1.22E+06	1.04E+06	6.57E+05	1.32E+05	1.33E+03	1.38E-04	1.53E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BA140	1.19E-03	6.57E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LA138	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07	9.85E-07
LA140	1.37E-03	7.57E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CE141	4.56E+02	7.81E-05	1.62E-28	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CE142	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09
CE144	1.63E+05	2.76E+04	5.50E+01	1.05E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR143	8.38E-03	5.32E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR144	1.63E+05	2.76E+04	5.50E+01	1.05E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR144M	2.45E+03	4.14E+02	8.25E-01	1.58E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ND144	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08	5.28E-08
PM147	8.21E+04	4.84E+04	7.61E+03	3.86E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SM147	1.20E-06	2.03E-06	3.04E-06	3.23E-06	3.23E-06	3.23E-06	3.23E-06	3.23E-06	3.23E-06	3.23E-06	3.23E-06	3.23E-06	3.23E-06
SM148	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09
SM149	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12	6.30E-12
SM151	5.92E+02	5.83E+02	5.52E+02	4.73E+02	2.76E+02	5.92E+01	2.70E-01	5.50E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU152	2.40E+00	2.16E+00	1.51E+00	5.42E-01	1.50E-02	5.29E-07	1.38E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU154	2.59E+04	2.20E+04	1.25E+04	2.49E+03	8.81E+00	8.70E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU155	1.28E+04	9.60E+03	3.53E+03	2.02E+02	9.03E-03	3.38E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU156	2.36E-01	7.79E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TB160	5.63E+04	5.11E+01	1.16E-09	4.43E-40	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG206	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.05E-10
TL206	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.44E-12	3.75E-11	7.60E-10	6.16E-09	3.65E-08	1.27E-07	2.83E-07	2.91E-07	4.97E-08
TL207	2.31E-12	2.04E-11	2.11E-10	1.57E-09	1.02E-08	3.92E-08	1.45E-07	4.26E-07	1.32E-06	3.27E-06	6.16E-06	7.01E-06	7.02E-06
TL208	2.03E-02	5.16E-02	9.54E-02	8.95E-02	4.47E-02	6.14E-03	5.88E-06	6.19E-10	4.76E-09	2.50E-08	1.07E-07	3.40E-07	1.15E-06
TL209	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.73E-10	9.84E-09	1.96E-07	2.72E-06	3.52E-05	2.50E-04	1.15E-03	2.65E-03	2.98E-03
TL210	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.54E-10	7.61E-09	1.19E-07	9.66E-07	5.73E-06	1.99E-05	4.44E-05	4.57E-05	7.79E-06
PB209	3.14E-12	2.96E-11	3.27E-10	2.88E-09	3.58E-08	4.56E-07	9.07E-06	1.26E-04	1.63E-03	1.16E-02	5.33E-02	1.23E-01	1.38E-01
PB210	5.42E-13	1.53E-11	6.41E-10	2.17E-08	1.07E-06	2.80E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02
PB211	2.31E-12	2.04E-11	2.11E-10	1.57E-09	1.03E-08	3.93E-08	1.45E-07	4.27E-07	1.33E-06	3.28E-06	6.18E-06	7.03E-06	7.04E-06

PB212	5.66E-02	1.43E-01	2.65E-01	2.49E-01	1.24E-01	1.71E-02	1.64E-05	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06
PB214	5.40E-11	5.21E-10	7.15E-09	9.76E-08	2.16E-06	3.62E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02

Base Case 40MT Life Engine DU Fuel 99% FIMA (cont.)

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
BI210	5.42E-13	1.53E-11	6.41E-10	2.17E-08	1.07E-06	2.80E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02
BI211	2.31E-12	2.04E-11	2.11E-10	1.57E-09	1.03E-08	3.93E-08	1.45E-07	4.27E-07	1.33E-06	3.28E-06	6.18E-06	7.03E-06	7.04E-06
BI212	5.66E-02	1.43E-01	2.65E-01	2.49E-01	1.24E-01	1.71E-02	1.64E-05	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06
BI213	3.14E-12	2.96E-11	3.27E-10	2.88E-09	3.58E-08	4.56E-07	9.07E-06	1.26E-04	1.63E-03	1.16E-02	5.33E-02	1.23E-01	1.38E-01
BI214	5.40E-11	5.21E-10	7.15E-09	9.76E-08	2.16E-06	3.63E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02
BI215	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.66E-12
PO210	1.75E-13	9.27E-12	6.41E-10	2.17E-08	1.07E-06	2.80E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02
PO211	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.80E-11	1.07E-10	3.97E-10	1.17E-09	3.62E-09	8.94E-09	1.69E-08	1.92E-08	1.92E-08
PO212	3.63E-02	9.19E-02	1.70E-01	1.60E-01	7.97E-02	1.09E-02	1.05E-05	1.10E-09	8.49E-09	4.45E-08	1.91E-07	6.06E-07	2.04E-06
PO213	3.07E-12	2.90E-11	3.20E-10	2.82E-09	3.50E-08	4.46E-07	8.88E-06	1.23E-04	1.59E-03	1.13E-02	5.22E-02	1.20E-01	1.35E-01
PO214	5.40E-11	5.21E-10	7.15E-09	9.76E-08	2.16E-06	3.62E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02
PO215	2.31E-12	2.04E-11	2.11E-10	1.57E-09	1.03E-08	3.93E-08	1.45E-07	4.27E-07	1.33E-06	3.28E-06	6.18E-06	7.03E-06	7.04E-06
PO216	5.66E-02	1.43E-01	2.65E-01	2.49E-01	1.24E-01	1.71E-02	1.64E-05	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06
PO218	5.40E-11	5.21E-10	7.15E-09	9.76E-08	2.16E-06	3.63E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02
AT215	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.82E-11
AT217	3.14E-12	2.96E-11	3.27E-10	2.88E-09	3.58E-08	4.56E-07	9.07E-06	1.26E-04	1.63E-03	1.16E-02	5.33E-02	1.23E-01	1.38E-01
AT218	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.33E-10	7.25E-09	1.14E-07	9.20E-07	5.46E-06	1.90E-05	4.23E-05	4.35E-05	7.42E-06
AT219	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.83E-12
RN217	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.30E-12	5.47E-11	1.09E-09	1.51E-08	1.95E-07	1.39E-06	6.40E-06	1.47E-05	1.65E-05
RN218	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.33E-13	7.25E-12	1.14E-10	9.20E-10	5.46E-09	1.90E-08	4.23E-08	4.35E-08	7.42E-09
RN219	2.31E-12	2.04E-11	2.11E-10	1.57E-09	1.03E-08	3.93E-08	1.45E-07	4.27E-07	1.33E-06	3.28E-06	6.18E-06	7.03E-06	7.04E-06
RN220	5.66E-02	1.43E-01	2.65E-01	2.49E-01	1.24E-01	1.71E-02	1.64E-05	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06
RN222	5.40E-11	5.21E-10	7.15E-09	9.76E-08	2.16E-06	3.63E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02
FR221	3.14E-12	2.96E-11	3.27E-10	2.88E-09	3.58E-08	4.56E-07	9.07E-06	1.26E-04	1.63E-03	1.16E-02	5.33E-02	1.23E-01	1.38E-01
FR223	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.41E-10	5.43E-10	2.00E-09	5.89E-09	1.83E-08	4.52E-08	8.52E-08	9.70E-08	9.72E-08
RA223	2.31E-12	2.04E-11	2.11E-10	1.57E-09	1.03E-08	3.93E-08	1.45E-07	4.27E-07	1.33E-06	3.28E-06	6.18E-06	7.03E-06	7.04E-06
RA224	5.66E-02	1.43E-01	2.65E-01	2.49E-01	1.24E-01	1.71E-02	1.64E-05	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06
RA225	3.14E-12	2.96E-11	3.27E-10	2.88E-09	3.58E-08	4.56E-07	9.07E-06	1.26E-04	1.63E-03	1.16E-02	5.33E-02	1.23E-01	1.38E-01
RA226	5.40E-11	5.21E-10	7.15E-09	9.76E-08	2.16E-06	3.63E-05	5.68E-04	4.60E-03	2.73E-02	9.49E-02	2.11E-01	2.18E-01	3.71E-02
RA228	3.14E-12	2.96E-11	3.27E-10	2.88E-09	1.31E-11	5.26E-11	2.86E-10	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06
AC225	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.58E-08	4.56E-07	9.07E-06	1.26E-04	1.63E-03	1.16E-02	5.33E-02	1.23E-01	1.38E-01

AC227	2.31E-12	2.04E-11	2.11E-10	1.57E-09	1.03E-08	3.93E-08	1.45E-07	4.27E-07	1.33E-06	3.28E-06	6.18E-06	7.03E-06	7.04E-06
AC228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.31E-11	5.26E-11	2.86E-10	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06

Base Case 40MT Life Engine DU Fuel 99% FIMA (cont.)

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
TH227	2.28E-12	2.02E-11	2.08E-10	1.55E-09	1.01E-08	3.88E-08	1.43E-07	4.21E-07	1.31E-06	3.23E-06	6.09E-06	6.93E-06	6.95E-06
TH228	5.66E-02	1.43E-01	2.65E-01	2.49E-01	1.24E-01	1.71E-02	1.64E-05	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06
TH229	3.14E-12	2.96E-11	3.27E-10	2.88E-09	3.58E-08	4.56E-07	9.07E-06	1.26E-04	1.63E-03	1.16E-02	5.33E-02	1.23E-01	1.38E-01
TH230	2.54E-07	8.43E-07	3.75E-06	1.88E-05	1.33E-04	7.25E-04	3.30E-03	1.07E-02	3.51E-02	9.43E-02	2.10E-01	2.17E-01	3.71E-02
TH231	6.94E-06	6.94E-06	6.94E-06	6.94E-06	6.94E-06	6.94E-06	6.94E-06	6.95E-06	6.96E-06	6.99E-06	7.04E-06	7.05E-06	7.04E-06
TH232	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.44E-11	5.26E-11	2.86E-10	1.72E-09	1.33E-08	6.95E-08	2.98E-07	9.47E-07	3.19E-06
TH234	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.50E-03	1.53E-03	1.64E-03	1.88E-03	2.28E-03
PA231	1.47E-10	4.41E-10	1.47E-09	4.41E-09	1.47E-08	4.39E-08	1.45E-07	4.27E-07	1.33E-06	3.28E-06	6.17E-06	7.03E-06	7.04E-06
PA233	1.48E-02	1.48E-02	1.50E-02	1.67E-02	2.49E-02	4.57E-02	8.50E-02	1.13E-01	1.41E-01	1.70E-01	1.73E-01	1.62E-01	1.29E-01
PA234	1.94E-06	1.94E-06	1.94E-06	1.94E-06	1.94E-06	1.94E-06	1.94E-06	1.94E-06	1.95E-06	1.99E-06	2.13E-06	2.45E-06	2.96E-06
PA234M	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.50E-03	1.53E-03	1.64E-03	1.88E-03	2.28E-03
U232	2.00E-01	2.40E-01	2.81E-01	2.42E-01	1.21E-01	1.66E-02	1.59E-05	3.78E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U233	6.56E-08	2.08E-07	6.76E-07	2.05E-06	8.36E-06	3.95E-05	2.48E-04	1.14E-03	5.01E-03	1.79E-02	5.89E-02	1.22E-01	1.37E-01
U234	2.91E-02	3.50E-02	5.52E-02	1.07E-01	2.36E-01	3.74E-01	4.09E-01	4.07E-01	3.99E-01	3.77E-01	3.10E-01	1.77E-01	2.64E-02
U235	6.94E-06	6.94E-06	6.94E-06	6.94E-06	6.94E-06	6.94E-06	6.94E-06	6.95E-06	6.96E-06	6.99E-06	7.04E-06	7.05E-06	7.04E-06
U236	2.71E-03	2.71E-03	2.72E-03	2.80E-03	3.22E-03	4.53E-03	8.92E-03	1.98E-02	4.40E-02	6.34E-02	6.60E-02	6.56E-02	6.44E-02
U237	2.92E-01	2.65E-01	1.90E-01	7.27E-02	2.97E-03	4.75E-04	4.49E-04	3.81E-04	2.15E-04	4.21E-05	1.40E-07	1.15E-14	0.00E+00
U238	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.49E-03	1.50E-03	1.53E-03	1.64E-03	1.88E-03	2.28E-03
U240	9.49E-05	9.50E-05	9.51E-05	9.54E-05	9.66E-05	1.00E-04	1.12E-04	1.45E-04	2.61E-04	5.83E-04	1.61E-03	3.85E-03	7.21E-03
NP237	1.48E-02	1.48E-02	1.50E-02	1.67E-02	2.49E-02	4.57E-02	8.50E-02	1.13E-01	1.41E-01	1.70E-01	1.73E-01	1.62E-01	1.29E-01
NP239	3.44E+01	3.44E+01	3.44E+01	3.43E+01	3.41E+01	3.34E+01	3.13E+01	2.59E+01	1.34E+01	2.06E+00	1.79E-02	1.49E-02	1.45E-02
NP240	9.49E-05	9.50E-05	9.51E-05	9.54E-05	9.66E-05	1.00E-04	1.12E-04	1.45E-04	2.61E-04	5.83E-04	1.61E-03	3.85E-03	7.21E-03
PU236	2.85E+00	1.77E+00	3.32E-01	2.79E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU237	1.55E-01	2.17E-06	2.23E-23	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU238	1.05E+03	1.05E+03	9.94E+02	8.49E+02	4.88E+02	1.00E+02	3.98E-01	5.44E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU239	1.72E+01	1.72E+01	1.72E+01	1.72E+01	1.73E+01	1.74E+01	1.77E+01	1.83E+01	1.84E+01	1.28E+01	1.84E+00	2.00E-02	1.45E-02
PU240	2.29E+01	3.79E+01	8.22E+01	1.59E+02	2.20E+02	2.20E+02	2.04E+02	1.65E+02	7.89E+01	9.55E+00	7.49E-03	3.85E-03	7.21E-03
PU241	1.19E+04	1.08E+04	7.73E+03	2.96E+03	1.21E+02	1.94E+01	1.83E+01	1.56E+01	8.79E+00	1.72E+00	5.70E-03	4.70E-10	0.00E+00
PU242	8.51E-01	8.55E-01	8.65E-01	8.95E-01	9.99E-01	1.29E+00	2.25E+00	4.49E+00	8.66E+00	1.05E+01	9.36E+00	6.46E+00	1.76E+00
PU243	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.49E-02	1.45E-02
PU244	9.51E-05	9.51E-05	9.52E-05	9.55E-05	9.68E-05	1.00E-04	1.12E-04	1.45E-04	2.61E-04	5.84E-04	1.61E-03	3.86E-03	7.22E-03

AM241	2.33E+01	5.96E+01	1.61E+02	3.12E+02	3.68E+02	2.75E+02	1.02E+02	1.96E+01	8.79E+00	1.72E+00	5.70E-03	4.95E-10	0.00E+00
AM243	3.44E+01	3.44E+01	3.44E+01	3.43E+01	3.41E+01	3.34E+01	3.13E+01	2.59E+01	1.34E+01	2.06E+00	1.79E-02	1.49E-02	1.45E-02

Base Case 40MT Life Engine DU Fuel 99% FIMA (cont.)

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
CM242	3.63E+03	1.62E+02	3.07E-03	9.84E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CM243	1.55E+01	1.48E+01	1.25E+01	7.91E+00	1.57E+00	1.54E-02	1.46E-09	1.24E-29	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CM244	7.38E+04	6.84E+04	5.23E+04	2.43E+04	1.67E+03	7.86E-01	1.79E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CM245	1.98E+01	1.98E+01	1.98E+01	1.98E+01	1.97E+01	1.94E+01	1.83E+01	1.55E+01	8.78E+00	1.72E+00	5.69E-03	4.69E-10	0.00E+00
CM246	8.13E+02	8.12E+02	8.11E+02	8.09E+02	8.01E+02	7.78E+02	7.02E+02	5.24E+02	1.88E+02	1.00E+01	3.53E-04	6.63E-17	0.00E+00
CM247	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.49E-02	1.45E-02
CM248	2.11E+00	2.11E+00	2.11E+00	2.11E+00	2.11E+00	2.11E+00	2.11E+00	2.10E+00	2.07E+00	1.99E+00	1.72E+00	1.15E+00	2.75E-01
Fission Products	5.72E+06	4.21E+06	2.95E+06	1.80E+06	3.50E+05	3.49E+03	7.19E+01	7.14E+01	7.09E+01	6.96E+01	6.56E+01	5.75E+01	4.15E+01
Actinides & Daughters	9.14E+04	8.14E+04	6.22E+04	2.95E+04	3.78E+03	1.50E+03	1.13E+03	8.17E+02	3.50E+02	5.60E+01	1.63E+01	1.16E+01	4.11E+00
Total	5.82E+06	4.29E+06	3.01E+06	1.82E+06	3.54E+05	4.99E+03	1.20E+03	8.89E+02	4.21E+02	1.26E+02	8.20E+01	6.91E+01	4.57E+01

Appendix C

Radionuclide Inventory as a Function of Time for 99.9% FIMA LIFE Fuel **Base Case 40MT Life Engine DU Fuel 99.9% FIMA**

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
SE 79	1.08E-01	1.08E-01	1.08E-01	1.08E-01	1.08E-01	1.08E-01	1.07E-01	1.05E-01	9.73E-02	7.86E-02	3.73E-02	4.41E-03	2.53E-06
KR 85	7.53E+04	6.62E+04	4.21E+04	1.16E+04	1.25E+02	3.03E-04	6.67E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RB 86	1.59E+00	2.60E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RB 87	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04	2.86E-04
SR 89	1.79E+03	7.93E-02	4.62E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SR 90	4.18E+05	3.98E+05	3.36E+05	2.07E+05	3.81E+04	3.01E+02	1.32E-05	1.25E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 89M	1.72E-01	7.64E-06	4.45E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 90	4.18E+05	3.98E+05	3.36E+05	2.07E+05	3.81E+04	3.01E+02	1.32E-05	1.25E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y 91	2.46E+03	4.28E-01	3.00E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ZR 93	1.79E+01	1.79E+01	1.79E+01	1.79E+01	1.79E+01	1.79E+01	1.79E+01	1.78E+01	1.78E+01	1.76E+01	1.71E+01	1.56E+01	1.14E+01
ZR 95	3.00E+04	1.10E+01	1.05E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NB 93M	7.32E-01	2.11E+00	6.08E+00	1.26E+01	1.72E+01	1.74E+01	1.74E+01	1.74E+01	1.73E+01	1.72E+01	1.66E+01	1.52E+01	1.11E+01
NB 95	6.65E+04	2.51E+01	2.32E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NB 95M	3.49E+02	1.28E-01	1.22E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TC 99	2.01E+00	2.01E+00	2.01E+00	2.01E+00	2.01E+00	2.01E+00	2.01E+00	1.99E+00	1.95E+00	1.83E+00	1.45E+00	7.53E-01	7.57E-02
RU103	5.69E+04	1.43E-01	3.54E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RU106	1.93E+05	4.89E+04	3.97E+02	4.23E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RH103M	5.63E+04	1.41E-01	3.51E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RH106	1.93E+05	4.89E+04	3.97E+02	4.23E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PD107	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.82E+00	1.81E+00	1.77E+00	1.64E+00
IN115	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12	1.16E-12
SN123	3.85E+03	7.63E+01	8.39E-05	7.93E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SN126	3.63E-02	3.63E-02	3.63E-02	3.62E-02	3.62E-02	3.62E-02	3.60E-02	3.55E-02	3.38E-02	2.94E-02	1.81E-02	4.53E-03	3.54E-05
SB124	9.09E+02	2.04E-01	3.41E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SB125	3.34E+04	2.02E+04	3.48E+03	2.29E+01	5.28E-07	7.97E-29	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SB126	5.28E-03	5.08E-03	5.08E-03	5.07E-03	5.07E-03	5.06E-03	5.04E-03	4.97E-03	4.74E-03	4.12E-03	2.54E-03	6.35E-04	4.96E-06
SB126M	3.63E-02	3.63E-02	3.63E-02	3.62E-02	3.62E-02	3.62E-02	3.60E-02	3.55E-02	3.38E-02	2.94E-02	1.81E-02	4.53E-03	3.54E-05
TE123	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10	2.12E-10
TE125M	8.24E+03	5.06E+03	8.72E+02	5.74E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I129	9.30E-02	9.30E-02	9.30E-02	9.30E-02	9.30E-02	9.30E-02	9.30E-02	9.30E-02	9.29E-02	9.28E-02	9.26E-02	9.18E-02	8.89E-02
CS134	2.81E+05	1.44E+05	1.37E+04	1.67E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CS135	9.10E+00	9.10E+00	9.10E+00	9.10E+00	9.10E+00	9.10E+00	9.10E+00	9.09E+00	9.08E+00	9.03E+00	8.84E+00	8.35E+00	6.82E+00

Base Case 40MT Life Engine DU Fuel 99.9% FIMA (cont.)

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
CS136	1.47E-01	1.97E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CS137	1.36E+06	1.30E+06	1.11E+06	6.99E+05	1.40E+05	1.41E+03	1.47E-04	1.62E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BA137M	1.29E+06	1.23E+06	1.05E+06	6.61E+05	1.32E+05	1.34E+03	1.39E-04	1.54E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BA140	8.09E-04	4.48E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LA138	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07	3.36E-07
LA140	9.31E-04	5.16E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CE141	2.84E+03	4.87E-04	1.01E-27	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CE142	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09
CE144	1.16E+05	1.97E+04	3.92E+01	7.51E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR143	5.62E-02	3.56E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR144	1.16E+05	1.97E+04	3.92E+01	7.52E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR144M	1.75E+03	2.95E+02	5.88E-01	1.13E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ND144	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08	5.69E-08
PM147	1.18E+05	6.93E+04	1.09E+04	5.52E+01	5.12E-07	5.72E-30	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SM147	9.81E-07	2.18E-06	3.62E-06	3.89E-06	3.89E-06	3.89E-06	3.89E-06	3.89E-06	3.89E-06	3.89E-06	3.89E-06	3.89E-06	3.89E-06
SM148	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09
SM149	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11	1.92E-11
SM151	2.85E+02	2.81E+02	2.66E+02	2.28E+02	1.33E+02	2.85E+01	1.30E-01	2.65E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU152	2.35E-01	2.12E-01	1.48E-01	5.32E-02	1.47E-03	5.18E-08	1.35E-23	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU154	6.62E+03	5.64E+03	3.20E+03	6.39E+02	2.26E+00	2.23E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU155	5.15E+03	3.87E+03	1.42E+03	8.14E+01	3.64E-03	1.36E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU156	5.17E-01	1.71E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TB160	5.59E+04	5.08E+01	1.15E-09	4.43E-40	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG206	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.77E-12
TL206	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.07E-10
TL207	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.99E-13	2.73E-12	1.08E-11	3.71E-11	1.76E-10	8.47E-10	3.27E-09	4.68E-09	4.98E-09
TL208	2.22E-05	1.14E-04	3.67E-04	3.88E-04	1.94E-04	2.67E-05	2.56E-08	1.65E-11	1.24E-10	6.46E-10	2.76E-09	8.80E-09	3.00E-08
TL209	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.16E-11	1.63E-10	3.56E-09	5.06E-08	6.26E-07	4.11E-06	1.78E-05	4.04E-05	4.53E-05
TL210	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.41E-13	1.82E-11	3.00E-10	2.46E-09	1.46E-08	5.11E-08	1.15E-07	1.27E-07	6.38E-08
PB209	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-10	7.55E-09	1.65E-07	2.34E-06	2.90E-05	1.90E-04	8.26E-04	1.87E-03	2.10E-03
PB210	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.14E-09	6.65E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
PB211	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.01E-13	2.74E-12	1.08E-11	3.73E-11	1.77E-10	8.49E-10	3.28E-09	4.69E-09	4.99E-09
PB212	6.17E-05	3.18E-04	1.02E-03	1.08E-03	5.41E-04	7.43E-05	7.11E-08	4.59E-11	3.46E-10	1.80E-09	7.69E-09	2.45E-08	8.34E-08

Base Case 40MT Life Engine DU Fuel 99.9% FIMA (cont.)

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
PB214	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.48E-09	8.66E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
BI210	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.14E-09	6.65E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
BI211	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.01E-13	2.74E-12	1.08E-11	3.73E-11	1.77E-10	8.49E-10	3.28E-09	4.69E-09	4.99E-09
BI212	6.17E-05	3.18E-04	1.02E-03	1.08E-03	5.41E-04	7.43E-05	7.11E-08	4.59E-11	3.46E-10	1.80E-09	7.69E-09	2.45E-08	8.34E-08
BI213	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.36E-10	7.55E-09	1.65E-07	2.34E-06	2.90E-05	1.90E-04	8.26E-04	1.87E-03	2.10E-03
BI214	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.48E-09	8.66E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
PO210	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.14E-09	6.65E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
PO211	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.36E-11
PO212	3.95E-05	2.04E-04	6.55E-04	6.92E-04	3.46E-04	4.75E-05	4.56E-08	2.94E-11	2.22E-10	1.15E-09	4.93E-09	1.57E-08	5.34E-08
PO213	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.25E-10	7.39E-09	1.61E-07	2.29E-06	2.84E-05	1.86E-04	8.08E-04	1.83E-03	2.05E-03
PO214	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.48E-09	8.66E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
PO215	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.01E-13	2.74E-12	1.08E-11	3.73E-11	1.77E-10	8.49E-10	3.28E-09	4.69E-09	4.99E-09
PO216	6.17E-05	3.18E-04	1.02E-03	1.08E-03	5.41E-04	7.43E-05	7.11E-08	4.59E-11	3.46E-10	1.80E-09	7.69E-09	2.45E-08	8.34E-08
PO218	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.48E-09	8.66E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
AT217	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-10	7.55E-09	1.65E-07	2.34E-06	2.90E-05	1.90E-04	8.26E-04	1.87E-03	2.10E-03
AT218	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.97E-13	1.73E-11	2.85E-10	2.34E-09	1.39E-08	4.86E-08	1.09E-07	1.21E-07	6.08E-08
RN217	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.51E-07
RN218	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.08E-11
RN219	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.01E-13	2.74E-12	1.08E-11	3.73E-11	1.77E-10	8.49E-10	3.28E-09	4.69E-09	4.99E-09
RN220	6.17E-05	3.18E-04	1.02E-03	1.08E-03	5.41E-04	7.43E-05	7.11E-08	4.59E-11	3.46E-10	1.80E-09	7.69E-09	2.45E-08	8.34E-08
RN222	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.48E-09	8.66E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
FR221	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-10	7.55E-09	1.65E-07	2.34E-06	2.90E-05	1.90E-04	8.26E-04	1.87E-03	2.10E-03
FR223	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.89E-11
RA223	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.01E-13	2.74E-12	1.08E-11	3.73E-11	1.77E-10	8.49E-10	3.28E-09	4.69E-09	4.99E-09
RA224	6.17E-05	3.18E-04	1.02E-03	1.08E-03	5.41E-04	7.43E-05	7.11E-08	4.59E-11	3.46E-10	1.80E-09	7.69E-09	2.45E-08	8.34E-08
RA225	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-10	7.55E-09	1.65E-07	2.34E-06	2.90E-05	1.90E-04	8.26E-04	1.87E-03	2.10E-03
RA226	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.48E-09	8.66E-08	1.43E-06	1.17E-05	6.97E-05	2.43E-04	5.47E-04	6.03E-04	3.04E-04
RA228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.34E-08
AC225	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-10	7.55E-09	1.65E-07	2.34E-06	2.90E-05	1.90E-04	8.26E-04	1.87E-03	2.10E-03
AC227	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.01E-13	2.74E-12	1.08E-11	3.73E-11	1.77E-10	8.49E-10	3.28E-09	4.69E-09	4.99E-09
AC228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.34E-08
TH227	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.91E-13	2.70E-12	1.06E-11	3.67E-11	1.74E-10	8.37E-10	3.24E-09	4.63E-09	4.92E-09
TH228	6.17E-05	3.17E-04	1.02E-03	1.08E-03	5.41E-04	7.43E-05	7.11E-08	4.59E-11	3.46E-10	1.80E-09	7.69E-09	2.45E-08	8.34E-08

Base Case 40MT Life Engine DU Fuel 99.9% FIMA (cont.)
Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
TH229	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-10	7.55E-09	1.65E-07	2.34E-06	2.90E-05	1.90E-04	8.26E-04	1.87E-03	2.10E-03
TH230	3.75E-11	3.10E-10	3.57E-09	3.13E-08	2.96E-07	1.78E-06	8.37E-06	2.72E-05	8.97E-05	2.42E-04	5.44E-04	6.02E-04	3.04E-04
TH231	4.71E-10	4.71E-10	4.72E-10	4.73E-10	4.80E-10	4.97E-10	5.60E-10	7.38E-10	1.34E-09	2.71E-09	4.40E-09	4.74E-09	4.99E-09
TH232	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.34E-08
TH234	6.92E-05	6.92E-05	6.92E-05	6.92E-05	6.92E-05	6.93E-05	6.93E-05	6.95E-05	7.15E-05	8.00E-05	1.10E-04	1.77E-04	2.84E-04
PA231	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E-12	3.06E-12	1.08E-11	3.72E-11	1.77E-10	8.49E-10	3.28E-09	4.69E-09	4.99E-09
PA233	2.08E-04	2.09E-04	2.14E-04	2.46E-04	4.13E-04	8.32E-04	1.60E-03	2.05E-03	2.34E-03	2.62E-03	2.63E-03	2.46E-03	1.96E-03
PA234	9.00E-08	9.00E-08	9.00E-08	9.00E-08	9.00E-08	9.00E-08	9.00E-08	9.03E-08	9.29E-08	1.04E-07	1.43E-07	2.30E-07	3.70E-07
PA234M	6.92E-05	6.92E-05	6.92E-05	6.92E-05	6.92E-05	6.93E-05	6.93E-05	6.95E-05	7.15E-05	8.00E-05	1.10E-04	1.77E-04	2.84E-04
U232	3.27E-04	7.09E-04	1.16E-03	1.05E-03	5.26E-04	7.22E-05	6.92E-08	1.64E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U233	9.47E-10	2.95E-09	9.56E-09	2.94E-08	1.29E-07	6.80E-07	4.58E-06	2.11E-05	8.74E-05	2.91E-04	9.09E-04	1.85E-03	2.08E-03
U234	7.17E-06	2.28E-05	7.79E-05	2.20E-04	5.71E-04	9.49E-04	1.04E-03	1.04E-03	1.02E-03	9.69E-04	8.13E-04	5.26E-04	2.95E-04
U235	4.71E-10	4.71E-10	4.72E-10	4.73E-10	4.80E-10	4.97E-10	5.60E-10	7.38E-10	1.34E-09	2.71E-09	4.40E-09	4.74E-09	4.99E-09
U236	8.13E-05	8.14E-05	8.17E-05	8.36E-05	9.45E-05	1.28E-04	2.41E-04	5.20E-04	1.14E-03	1.64E-03	1.70E-03	1.70E-03	1.72E-03
U237	5.99E-03	5.44E-03	3.88E-03	1.49E-03	5.57E-05	4.71E-06	4.45E-06	3.78E-06	2.14E-06	4.18E-07	1.39E-09	1.14E-16	0.00E+00
U238	6.92E-05	6.92E-05	6.92E-05	6.92E-05	6.92E-05	6.93E-05	6.93E-05	6.95E-05	7.15E-05	8.00E-05	1.10E-04	1.77E-04	2.84E-04
U240	4.13E-05	4.13E-05	4.13E-05	4.15E-05	4.19E-05	4.33E-05	4.82E-05	6.19E-05	1.10E-04	2.42E-04	6.66E-04	1.59E-03	2.97E-03
NP237	2.08E-04	2.09E-04	2.14E-04	2.46E-04	4.13E-04	8.32E-04	1.60E-03	2.05E-03	2.34E-03	2.62E-03	2.63E-03	2.46E-03	1.96E-03
NP239	8.99E-01	8.99E-01	8.99E-01	8.97E-01	8.91E-01	8.75E-01	8.19E-01	6.79E-01	3.53E-01	5.65E-02	3.33E-03	3.23E-03	3.13E-03
NP240	4.13E-05	4.13E-05	4.13E-05	4.15E-05	4.19E-05	4.33E-05	4.82E-05	6.19E-05	1.10E-04	2.42E-04	6.66E-04	1.59E-03	2.97E-03
PU236	2.49E-02	1.54E-02	2.89E-03	2.43E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU237	4.80E-03	6.71E-08	6.87E-25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU238	2.51E+00	2.85E+00	2.72E+00	2.32E+00	1.33E+00	2.75E-01	1.09E-03	1.49E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PU239	7.84E-01	7.84E-01	7.84E-01	7.84E-01	7.85E-01	7.85E-01	7.86E-01	7.84E-01	7.31E-01	4.76E-01	6.96E-02	3.28E-03	3.13E-03
PU240	7.90E-01	1.16E+00	2.25E+00	4.15E+00	5.65E+00	5.64E+00	5.24E+00	4.24E+00	2.03E+00	2.45E-01	8.17E-04	1.59E-03	2.97E-03
PU241	2.44E+02	2.22E+02	1.58E+02	6.06E+01	2.27E+00	1.92E-01	1.82E-01	1.54E-01	8.72E-02	1.71E-02	5.66E-05	4.66E-12	0.00E+00
PU242	2.63E-02	2.71E-02	3.03E-02	3.91E-02	6.99E-02	1.56E-01	4.39E-01	1.10E+00	2.33E+00	2.89E+00	2.57E+00	1.78E+00	4.84E-01
PU243	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.26E-03	3.23E-03	3.13E-03
PU244	4.13E-05	4.13E-05	4.14E-05	4.15E-05	4.20E-05	4.34E-05	4.82E-05	6.20E-05	1.10E-04	2.43E-04	6.67E-04	1.59E-03	2.98E-03
AM241	4.05E-01	1.15E+00	3.23E+00	6.33E+00	7.46E+00	5.52E+00	1.92E+00	2.31E-01	8.72E-02	1.71E-02	5.66E-05	4.91E-12	0.00E+00
AM243	8.99E-01	8.99E-01	8.99E-01	8.97E-01	8.91E-01	8.75E-01	8.19E-01	6.79E-01	3.53E-01	5.65E-02	3.33E-03	3.23E-03	3.13E-03
CM242	7.97E+01	3.56E+00	6.75E-05	2.16E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CM243	2.18E-01	2.08E-01	1.77E-01	1.12E-01	2.21E-02	2.18E-04	2.06E-11	1.76E-31	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Base Case 40MT Life Engine DU Fuel 99.9% FIMA (cont.)

Curies per Metric Ton Initial Heavy Metal

	Years since discharge												
Nuclide	1.E+00	3.E+00	1.E+01	3.E+01	1.E+02	3.E+02	1.E+03	3.E+03	1.E+04	3.E+04	1.E+05	3.E+05	1.E+06
CM244	1.82E+03	1.69E+03	1.29E+03	5.99E+02	4.11E+01	1.94E-02	4.42E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CM245	1.97E-01	1.97E-01	1.97E-01	1.96E-01	1.95E-01	1.92E-01	1.81E-01	1.54E-01	8.70E-02	1.70E-02	5.65E-05	4.65E-12	0.00E+00
CM246	2.40E+02	2.39E+02	2.39E+02	2.39E+02	2.36E+02	2.29E+02	2.07E+02	1.54E+02	5.53E+01	2.95E+00	1.04E-04	1.95E-17	0.00E+00
CM247	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.27E-03	3.26E-03	3.23E-03	3.13E-03
CM248	8.70E-01	8.70E-01	8.70E-01	8.70E-01	8.70E-01	8.70E-01	8.68E-01	8.65E-01	8.53E-01	8.18E-01	7.09E-01	4.72E-01	1.13E-01
Fission Products	4.91E+06	3.78E+06	2.90E+06	1.79E+06	3.49E+05	3.43E+03	4.86E+01	4.84E+01	4.82E+01	4.77E+01	4.60E+01	4.18E+01	3.10E+01
Actinides & Daughters	2.39E+03	2.16E+03	1.70E+03	9.15E+02	2.98E+02	2.45E+02	2.18E+02	1.63E+02	6.23E+01	7.57E+00	3.39E+00	2.30E+00	6.54E-01
Total	4.91E+06	3.78E+06	2.90E+06	1.79E+06	3.49E+05	3.67E+03	2.67E+02	2.12E+02	1.10E+02	5.53E+01	4.94E+01	4.41E+01	3.17E+01

Appendix D

Radionuclide Inventory as a Function of Time for Average LWR Fuel

Average LWR Spent Fuel

	Years since discharge										
Nuclide	30	50	100	300	1000	3000	10000	30000	100000	300000	1000000
c14	1.509E+00	1.505E+00	1.496E+00	1.460E+00	1.342E+00	1.053E+00	4.516E-01	4.016E-02	8.423E-06	2.606E-16	0.000E+00
cl36	1.190E-02	1.190E-02	1.190E-02	1.189E-02	1.187E-02	1.182E-02	1.163E-02	1.111E-02	9.453E-03	5.964E-03	1.190E-03
fe55	1.128E+00	7.024E-03	2.151E-08	1.892E-30							
co60	1.708E+02	1.230E+01	1.712E-02	6.423E-14							
ni59	2.540E+00	2.539E+00	2.538E+00	2.534E+00	2.517E+00	2.471E+00	2.316E+00	1.925E+00	1.008E+00	1.588E-01	2.461E-04
ni63	3.325E+02	2.895E+02	2.048E+02	5.126E+01	4.023E-01	3.887E-07	3.447E-28	0.000E+00	0.000E+00	0.000E+00	0.000E+00
se79	4.760E-01	4.760E-01	4.759E-01	4.757E-01	4.749E-01	4.727E-01	4.650E-01	4.436E-01	3.762E-01	2.350E-01	4.530E-02
kr85	1.475E+03	4.048E+02	1.596E+01	3.857E-05							
sr90	4.006E+04	2.448E+04	7.147E+03	5.190E+01	1.693E-06	6.904E-28	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
y90	4.007E+04	2.449E+04	7.149E+03	5.191E+01	1.694E-06	6.905E-28	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
zr93	2.540E+00	2.540E+00	2.540E+00	2.540E+00	2.539E+00	2.537E+00	2.529E+00	2.506E+00	2.428E+00	2.217E+00	1.615E+00
nb93m	1.955E+00	2.292E+00	2.511E+00	2.541E+00	2.539E+00	2.537E+00	2.529E+00	2.506E+00	2.428E+00	2.217E+00	1.615E+00
nb94	8.888E-01	8.882E-01	8.867E-01	8.806E-01	8.598E-01	8.031E-01	6.323E-01	3.194E-01	2.925E-02	3.163E-05	1.314E-15
tc99	1.510E+01	1.510E+01	1.510E+01	1.509E+01	1.505E+01	1.495E+01	1.461E+01	1.368E+01	1.087E+01	5.639E+00	5.661E-01
ru106	6.318E-04	7.586E-10	1.199E-24	0.000E+00							
rh106	6.318E-04	7.586E-10	1.199E-24	0.000E+00							
pd107	1.400E-01	1.400E-01	1.400E-01	1.400E-01	1.400E-01	1.400E-01	1.399E-01	1.396E-01	1.385E-01	1.356E-01	1.258E-01
cd113m	1.687E+01	6.311E+00	5.401E-01	2.898E-05							
sn126	9.370E-01	9.368E-01	9.365E-01	9.352E-01	9.307E-01	9.179E-01	8.744E-01	7.612E-01	4.685E-01	1.171E-01	9.146E-04
sb125	9.654E+00	6.013E-02	1.842E-07	1.620E-29							
sb126	1.312E-01	1.312E-01	1.311E-01	1.309E-01	1.303E-01	1.285E-01	1.224E-01	1.066E-01	6.560E-02	1.640E-02	1.280E-04
sb126m	9.370E-01	9.368E-01	9.365E-01	9.352E-01	9.307E-01	9.179E-01	8.744E-01	7.612E-01	4.685E-01	1.171E-01	9.146E-04
te125m	2.357E+00	1.469E-02	4.497E-08	3.956E-30							
I129	3.810E-02	3.810E-02	3.810E-02	3.810E-02	3.810E-02	3.810E-02	3.808E-02	3.805E-02	3.793E-02	3.760E-02	3.645E-02
cs134	8.755E+00	1.052E-02	5.272E-10	0.000E+00							
cs135	5.710E-01	5.710E-01	5.710E-01	5.710E-01	5.708E-01	5.705E-01	5.693E-01	5.659E-01	5.541E-01	5.216E-01	4.224E-01
cs137	6.074E+04	3.826E+04	1.205E+04	1.186E+02	1.120E-05	9.518E-26	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
ba137m	5.735E+04	3.613E+04	1.138E+04	1.120E+02	1.058E-05	8.988E-26	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
pm147	4.497E+01	2.277E-01	4.155E-07	4.604E-30							
sm151	3.762E+02	3.225E+02	2.194E+02	4.701E+01	2.141E-01	4.369E-08	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
eu154	1.080E+03	2.151E+02	3.808E+00	3.739E-07							
eu155	1.237E+02	6.397E+00	3.886E-03	5.293E-16							

tl207					3.607E-04	1.033E-03	3.381E-03	9.694E-03	2.327E-02	2.907E-02	2.916E-02
tl208	1.304E-02	1.167E-02	7.104E-03	9.750E-04							
pb209					1.570E-04	1.843E-03	2.021E-02	1.196E-01	4.771E-01	1.059E+00	1.172E+00
pb210					1.022E-01	2.345E-01	4.426E-01	8.482E-01	1.530E+00	1.571E+00	5.204E-01
pb211					3.617E-04	1.036E-03	3.391E-03	9.721E-03	2.333E-02	2.915E-02	2.924E-02
pb212	3.628E-02	3.248E-02	1.977E-02	2.713E-03							
pb214					1.022E-01	2.346E-01	4.427E-01	8.483E-01	1.530E+00	1.572E+00	5.205E-01
bi210					1.022E-01	2.345E-01	4.426E-01	8.482E-01	1.530E+00	1.571E+00	5.204E-01
bi211					3.617E-04	1.036E-03	3.391E-03	9.721E-03	2.333E-02	2.915E-02	2.924E-02
bi212	3.628E-02	3.248E-02	1.977E-02	2.713E-03							
bi213					1.570E-04	1.843E-03	2.021E-02	1.196E-01	4.771E-01	1.059E+00	1.172E+00
bi214					1.022E-01	2.346E-01	4.427E-01	8.483E-01	1.530E+00	1.572E+00	5.205E-01
po210					1.022E-01	2.345E-01	4.426E-01	8.482E-01	1.530E+00	1.571E+00	5.204E-01
po212	2.324E-02	2.080E-02	1.266E-02	1.738E-03							
po213					1.537E-04	1.804E-03	1.979E-02	1.171E-01	4.671E-01	1.037E+00	1.148E+00
po214					1.022E-01	2.345E-01	4.426E-01	8.482E-01	1.530E+00	1.571E+00	5.204E-01
po215					3.617E-04	1.036E-03	3.391E-03	9.721E-03	2.333E-02	2.915E-02	2.924E-02
po216	3.628E-02	3.248E-02	1.977E-02	2.713E-03							
po218					1.022E-01	2.346E-01	4.428E-01	8.485E-01	1.531E+00	1.572E+00	5.206E-01
at217					1.570E-04	1.843E-03	2.022E-02	1.196E-01	4.771E-01	1.059E+00	1.172E+00
rn219					3.617E-04	1.036E-03	3.391E-03	9.721E-03	2.333E-02	2.915E-02	2.924E-02
rn220	3.628E-02	3.248E-02	1.977E-02	2.713E-03							
rn222					1.022E-01	2.346E-01	4.428E-01	8.485E-01	1.531E+00	1.572E+00	5.206E-01
fr221					1.570E-04	1.843E-03	2.022E-02	1.196E-01	4.771E-01	1.059E+00	1.172E+00
ra223					3.617E-04	1.036E-03	3.391E-03	9.721E-03	2.333E-02	2.915E-02	2.924E-02
ra224	3.628E-02	3.248E-02	1.977E-02	2.713E-03							
ra225					1.570E-04	1.843E-03	2.022E-02	1.196E-01	4.771E-01	1.059E+00	1.172E+00
ra226					1.022E-01	2.346E-01	4.428E-01	8.485E-01	1.531E+00	1.572E+00	5.206E-01
ac225					1.570E-04	1.843E-03	2.022E-02	1.196E-01	4.771E-01	1.059E+00	1.172E+00
ac227					3.617E-04	1.036E-03	3.391E-03	9.721E-03	2.333E-02	2.915E-02	2.924E-02
th227					3.567E-04	1.021E-03	3.344E-03	9.586E-03	2.301E-02	2.875E-02	2.884E-02
th228	3.625E-02	3.247E-02	1.977E-02	2.713E-03							
th229					1.570E-04	1.843E-03	2.022E-02	1.196E-01	4.771E-01	1.059E+00	1.172E+00
th230	2.861E-01	2.863E-01	2.870E-01	2.907E-01	3.059E-01	3.491E-01	4.924E-01	8.395E-01	1.521E+00	1.567E+00	5.206E-01
th231	1.590E-02	1.591E-02	1.593E-02	1.600E-02	1.626E-02	1.697E-02	1.918E-02	2.357E-02	2.850E-02	2.926E-02	2.924E-02
th234	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.171E-01	3.171E-01

pa231					3.616E-04	1.035E-03	3.390E-03	9.719E-03	2.333E-02	2.915E-02	2.924E-02
pa233	4.844E-01	5.123E-01	5.874E-01	8.435E-01	1.301E+00	1.512E+00	1.518E+00	1.509E+00	1.476E+00	1.383E+00	1.102E+00
pa234					4.121E-04	4.121E-04	4.121E-04	4.121E-04	4.121E-04	4.122E-04	4.122E-04
pa234m	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.171E-01	3.171E-01
U232	3.853E-02	3.159E-02	1.923E-02	2.639E-03							
u233					4.256E-03	1.684E-02	6.193E-02	1.830E-01	5.268E-01	1.047E+00	1.170E+00
U234	1.403E+00	1.591E+00	1.950E+00	2.536E+00	2.683E+00	2.671E+00	2.625E+00	2.498E+00	2.107E+00	1.335E+00	4.584E-01
U235	1.590E-02	1.591E-02	1.593E-02	1.600E-02	1.626E-02	1.697E-02	1.918E-02	2.357E-02	2.850E-02	2.926E-02	2.924E-02
U236	2.861E-01	2.865E-01	2.873E-01	2.907E-01	3.018E-01	3.295E-01	3.911E-01	4.403E-01	4.462E-01	4.436E-01	4.345E-01
U237	8.669E-01	3.299E-01	2.947E-02	1.264E-05							
U238	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.170E-01	3.171E-01	3.171E-01
np237	4.844E-01	5.123E-01	5.874E-01	8.435E-01	1.301E+00	1.512E+00	1.518E+00	1.509E+00	1.476E+00	1.383E+00	1.102E+00
np239	3.018E+01	3.012E+01	2.998E+01	2.942E+01	2.755E+01	2.283E+01	1.182E+01	1.801E+00	2.491E-03	1.688E-11	0.000E+00
pu238	3.605E+03	3.078E+03	2.073E+03	4.268E+02	1.689E+00	2.307E-07	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
pu239	3.809E+02	3.807E+02	3.802E+02	3.782E+02	3.713E+02	3.519E+02	2.908E+02	1.657E+02	2.225E+01	7.077E-02	1.284E-10
pu240	5.718E+02	5.727E+02	5.713E+02	5.596E+02	5.198E+02	4.208E+02	2.009E+02	2.429E+01	1.494E-02	9.986E-12	0.000E+00
pu241	3.622E+04	1.378E+04	1.231E+03	5.289E-01	4.255E-01	3.614E-01	2.042E-01	3.996E-02	1.324E-04	1.090E-11	0.000E+00
pu242	2.220E+00	2.220E+00	2.220E+00	2.219E+00	2.216E+00	2.208E+00	2.180E+00	2.101E+00	1.845E+00	1.273E+00	3.474E-01
am241	3.932E+03	4.538E+03	4.583E+03	3.357E+03	1.094E+03	4.471E+01	2.048E-01	3.996E-02	1.324E-04	1.148E-11	0.000E+00
am243	3.018E+01	3.012E+01	2.998E+01	2.942E+01	2.755E+01	2.283E+01	1.182E+01	1.801E+00	2.491E-03	1.688E-11	0.000E+00
cm242	3.912E-04	1.251E-17	0.000E+00	0.000E+00							
cm243	1.738E+01	1.068E+01	3.166E+00	2.443E-02							
cm244	1.453E+03	6.756E+02	9.955E+01	4.694E-02							
cm245	4.597E-01	4.590E-01	4.571E-01	4.497E-01	4.248E-01	3.608E-01	2.039E-01	3.989E-02	1.322E-04	1.088E-11	0.000E+00
cm246	9.990E-02	9.961E-02	9.888E-02	9.602E-02	8.666E-02	6.465E-02	2.318E-02	1.237E-03	4.346E-08	8.152E-21	0.000E+00

Appendix E

Elemental Composition (moles per mole initial U) of LIFE Fuel as a Function of Burnup

		Moles per Mole of Initial U at indicated % FIMA						
Element	**0%**	**20%**	**40%**	**60%**	**80%**	**95%**	**99%**	**99.9%**
Se		5.38E-04	1.07E-03	1.59E-03	2.12E-03	2.50E-03	2.59E-03	2.56E-03
Br		1.53E-04	2.47E-04	3.08E-04	3.42E-04	3.22E-04	2.67E-04	1.84E-04
Kr		3.61E-03	7.11E-03	1.05E-02	1.38E-02	1.63E-02	1.70E-02	1.72E-02
Rb		3.09E-03	6.03E-03	8.82E-03	1.16E-02	1.34E-02	1.37E-02	1.31E-02
Sr		6.41E-03	1.18E-02	1.64E-02	2.07E-02	2.32E-02	2.36E-02	2.41E-02
Y		3.56E-03	6.97E-03	1.02E-02	1.35E-02	1.59E-02	1.63E-02	1.53E-02
Zr		3.63E-02	7.20E-02	1.07E-01	1.43E-01	1.70E-01	1.76E-01	1.77E-01
Nb		1.02E-04	1.00E-04	9.96E-05	1.00E-04	5.66E-05	4.18E-05	7.58E-05
Mo		4.26E-02	8.45E-02	1.25E-01	1.65E-01	1.93E-01	1.99E-01	1.95E-01
Tc		6.85E-03	1.01E-02	1.06E-02	8.95E-03	4.34E-03	1.26E-03	2.00E-04
Ru		4.42E-02	9.01E-02	1.37E-01	1.85E-01	2.21E-01	2.28E-01	2.18E-01
Rh		4.11E-03	6.53E-03	6.88E-03	4.72E-03	1.19E-03	2.01E-04	7.16E-05
Pd		3.31E-02	6.69E-02	1.01E-01	1.35E-01	1.58E-01	1.58E-01	1.52E-01
Ag		2.28E-03	4.01E-03	4.67E-03	4.24E-03	2.31E-03	1.18E-03	5.57E-04
Cd		6.15E-03	1.65E-02	3.10E-02	5.01E-02	7.10E-02	8.28E-02	9.38E-02
In		4.81E-05	6.47E-05	5.59E-05	3.22E-05	7.51E-06	1.09E-06	3.40E-07
Sn		1.34E-03	2.71E-03	4.11E-03	5.56E-03	6.57E-03	6.77E-03	6.72E-03
Sb		3.51E-04	4.91E-04	5.45E-04	5.25E-04	3.47E-04	2.03E-04	1.28E-04
Te		6.57E-03	1.33E-02	2.00E-02	2.68E-02	3.19E-02	3.31E-02	3.28E-02
I		2.98E-03	5.16E-03	6.75E-03	7.85E-03	7.51E-03	5.33E-03	1.09E-03
Xe		4.82E-02	9.50E-02	1.41E-01	1.89E-01	2.26E-01	2.34E-01	2.34E-01
Cs		3.10E-02	5.30E-02	6.72E-02	7.44E-02	6.77E-02	5.80E-02	4.39E-02
Ba		2.05E-02	5.23E-02	9.23E-02	1.40E-01	1.88E-01	2.12E-01	2.32E-01
La		1.11E-02	2.17E-02	3.15E-02	4.04E-02	4.49E-02	4.14E-02	2.49E-02
Ce		2.14E-02	4.27E-02	6.42E-02	8.71E-02	1.05E-01	1.14E-01	1.29E-01
Pr		9.83E-03	1.85E-02	2.58E-02	3.19E-02	3.39E-02	2.97E-02	1.53E-02
Nd		3.26E-02	6.63E-02	1.00E-01	1.35E-01	1.62E-01	1.72E-01	1.85E-01
Pm		4.94E-04	5.63E-04	5.35E-04	4.59E-04	2.26E-04	1.55E-04	9.51E-05
Sm		6.42E-03	1.18E-02	1.54E-02	1.67E-02	1.51E-02	1.25E-02	1.06E-02
Eu		2.07E-03	3.51E-03	4.34E-03	4.08E-03	2.01E-03	7.34E-04	2.36E-04
Gd		3.21E-03	9.09E-03	1.70E-02	2.67E-02	3.45E-02	3.50E-02	2.61E-02
Tb		1.17E-04	4.12E-04	1.02E-03	2.01E-03	3.07E-03	3.24E-03	2.77E-03
Dy		1.19E-04	5.80E-04	1.77E-03	3.81E-03	4.52E-03	2.81E-03	1.46E-03
Ho		0.00E+00	1.86E-05	9.95E-05	6.24E-04	1.80E-03	2.02E-03	1.32E-03
Er		0.00E+00	8.28E-06	1.36E-04	1.09E-03	6.15E-03	1.43E-02	2.39E-02
U	1.00	6.41E-01	4.16E-01	2.43E-01	1.06E-01	2.43E-02	4.49E-03	2.07E-04
Np		1.49E-03	1.33E-03	9.11E-04	4.73E-04	1.56E-04	3.92E-05	6.96E-06
Pu		1.48E-01	1.64E-01	1.34E-01	6.87E-02	1.17E-02	7.15E-04	1.95E-05
Am		5.40E-03	9.46E-03	1.06E-02	7.53E-03	1.78E-03	1.69E-04	4.31E-06
Cm		2.96E-03	5.59E-03	7.93E-03	8.97E-03	5.90E-03	2.22E-03	5.37E-04
Bk			1.20E-06	4.96E-06	1.12E-05	1.33E-05	7.84E-06	5.67E-07
Cf			8.93E-07	1.57E-05	2.94E-05	3.61E-05	4.96E-05	5.09E-06
Es							4.55E-07	2.13E-07
Total	1.00	1.19	1.38	1.57	1.75	1.88	1.91	1.88

Appendix F

Elemental Composition (moles fraction) of LIFE Fuel as a Function of Burnup

	Mole Fraction Element at Indicated % FIMA (Heavy metal basis)							
Element	**0%**	**20%**	**40%**	**60%**	**80%**	**95%**	**99%**	**99.9%**
Se		4.52E-04	7.76E-04	1.02E-03	1.21E-03	1.33E-03	1.36E-03	1.36E-03
Br		1.28E-04	1.79E-04	1.97E-04	1.96E-04	1.71E-04	1.40E-04	9.80E-05
Kr		3.04E-03	5.15E-03	6.69E-03	7.90E-03	8.66E-03	8.89E-03	9.15E-03
Rb		2.59E-03	4.38E-03	5.64E-03	6.61E-03	7.14E-03	7.19E-03	6.96E-03
Sr		5.38E-03	8.54E-03	1.05E-02	1.18E-02	1.23E-02	1.24E-02	1.28E-02
Y		2.99E-03	5.05E-03	6.54E-03	7.69E-03	8.43E-03	8.55E-03	8.16E-03
Zr		3.05E-02	5.22E-02	6.86E-02	8.16E-02	9.01E-02	9.25E-02	9.41E-02
Nb		8.58E-05	7.27E-05	6.36E-05	5.72E-05	3.01E-05	2.19E-05	4.03E-05
Mo		3.58E-02	6.13E-02	7.98E-02	9.42E-02	1.03E-01	1.04E-01	1.03E-01
Tc		5.76E-03	7.32E-03	6.79E-03	5.12E-03	2.31E-03	6.62E-04	1.06E-04
Ru		3.72E-02	6.53E-02	8.75E-02	1.06E-01	1.17E-01	1.20E-01	1.16E-01
Rh		3.45E-03	4.74E-03	4.39E-03	2.70E-03	6.30E-04	1.05E-04	3.81E-05
Pd		2.78E-02	4.85E-02	6.43E-02	7.71E-02	8.37E-02	8.31E-02	8.10E-02
Ag		1.91E-03	2.91E-03	2.99E-03	2.42E-03	1.23E-03	6.18E-04	2.96E-04
Cd		5.17E-03	1.20E-02	1.98E-02	2.86E-02	3.77E-02	4.34E-02	4.98E-02
In		4.04E-05	4.69E-05	3.57E-05	1.84E-05	3.99E-06	5.70E-07	1.81E-07
Sn		1.13E-03	1.96E-03	2.63E-03	3.18E-03	3.49E-03	3.55E-03	3.57E-03
Sb		2.95E-04	3.56E-04	3.48E-04	3.00E-04	1.84E-04	1.06E-04	6.79E-05
Te		5.52E-03	9.64E-03	1.28E-02	1.53E-02	1.69E-02	1.74E-02	1.74E-02
I		2.50E-03	3.74E-03	4.31E-03	4.49E-03	3.99E-03	2.79E-03	5.80E-04
Xe		4.05E-02	6.89E-02	9.03E-02	1.08E-01	1.20E-01	1.23E-01	1.25E-01
Cs		2.60E-02	3.85E-02	4.30E-02	4.25E-02	3.59E-02	3.04E-02	2.33E-02
Ba		1.73E-02	3.80E-02	5.89E-02	8.00E-02	9.99E-02	1.11E-01	1.23E-01
La		9.36E-03	1.57E-02	2.01E-02	2.31E-02	2.38E-02	2.17E-02	1.32E-02
Ce		1.80E-02	3.09E-02	4.10E-02	4.97E-02	5.60E-02	5.98E-02	6.84E-02
Pr		8.26E-03	1.34E-02	1.65E-02	1.82E-02	1.80E-02	1.56E-02	8.12E-03
Nd		2.74E-02	4.81E-02	6.39E-02	7.70E-02	8.61E-02	9.03E-02	9.81E-02
Pm		4.15E-04	4.08E-04	3.42E-04	2.62E-04	1.20E-04	8.14E-05	5.05E-05
Sm		5.39E-03	8.54E-03	9.83E-03	9.55E-03	8.01E-03	6.57E-03	5.64E-03
Eu		1.74E-03	2.55E-03	2.77E-03	2.33E-03	1.07E-03	3.85E-04	1.26E-04
Gd		2.69E-03	6.59E-03	1.08E-02	1.52E-02	1.83E-02	1.83E-02	1.39E-02
Tb		9.84E-05	2.99E-04	6.53E-04	1.15E-03	1.63E-03	1.70E-03	1.47E-03
Dy		1.00E-04	4.21E-04	1.13E-03	2.17E-03	2.40E-03	1.47E-03	7.75E-04
Ho		0.00E+00	1.35E-05	6.36E-05	3.56E-04	9.55E-04	1.06E-03	7.03E-04
Er		0.00E+00	6.00E-06	8.69E-05	6.21E-04	3.27E-03	7.47E-03	1.27E-02
U	1.00	5.38E-01	3.02E-01	1.55E-01	6.07E-02	1.29E-02	2.35E-03	1.10E-04
Np		1.25E-03	9.62E-04	5.82E-04	2.70E-04	8.30E-05	2.06E-05	3.70E-06
Pu		1.24E-01	1.19E-01	8.54E-02	3.93E-02	6.20E-03	3.75E-04	1.03E-05
Am		4.54E-03	6.86E-03	6.79E-03	4.30E-03	9.45E-04	8.88E-05	2.29E-06
Cm		3.52E-03	7.71E-03	1.24E-02	1.57E-02	1.11E-02	4.24E-03	1.01E-03
Bk			1.66E-06	7.77E-06	1.96E-05	2.51E-05	1.50E-05	1.07E-06
Cf			1.23E-06	2.46E-05	5.14E-05	6.80E-05	9.46E-05	9.59E-06
Es							8.69E-07	4.00E-07